

Wide-Bandgap Power Semiconductor Research at Sandia National Laboratories

**Bob Kaplar, Matt Marinella, Sandeepan DasGupta,
David Hughart, Laura Biedermann, Stan Atcitty, and
Jerry Simmons**

**Presented at Auburn University
Physics Department Colloquium**

March 22, 2013



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Sandia's History



exceptional service in the national interest.



THE WHITE HOUSE
WASHINGTON
May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract to do the work on the atomic bomb at the laboratory at Los Alamos, New Mexico.

This cooperation, which is a vital part of the atomic energy program, should be of great value to the national defense, and should have the full support of the national defense.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Mr. C. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
155 Broadway,
New York 7, N. Y.



Sandia's Governance Structure



Government owned, contractor operated



Sandia Corporation

- AT&T: 1949–1993
- Martin Marietta: 1993–1995
- Lockheed Martin: 1995–present



Federally funded
research and development center



Sandia's Sites

Albuquerque,
New Mexico



Waste Isolation Pilot Plant,
Carlsbad, New Mexico



Livermore,
California



Tonopah, Nevada



Pantex, Texas



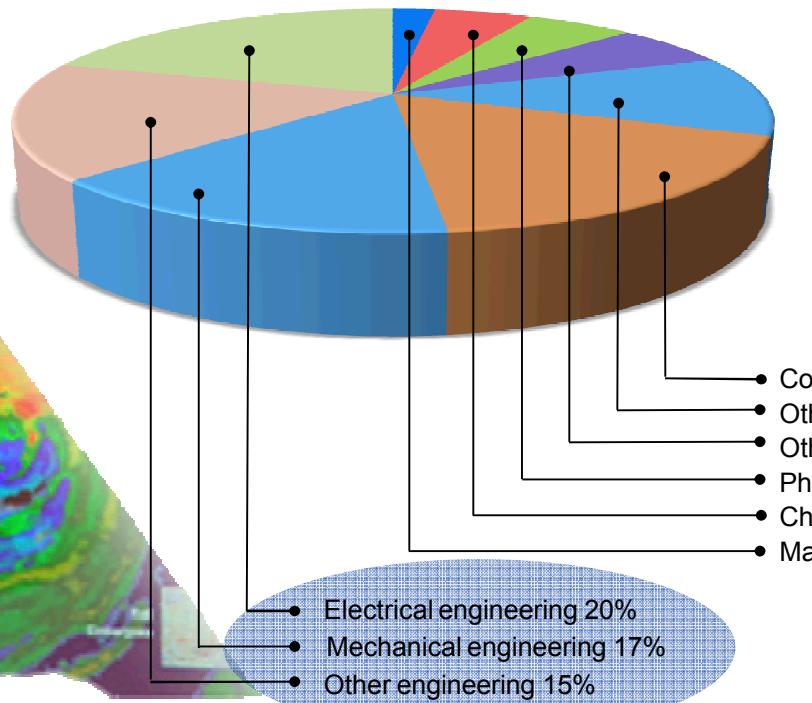
Kauai, Hawaii



People and Budget

- On-site workforce: 10,605
- Regular employees: 8,859
- Gross payroll: ~\$943 million

Technical staff (4,344) by discipline

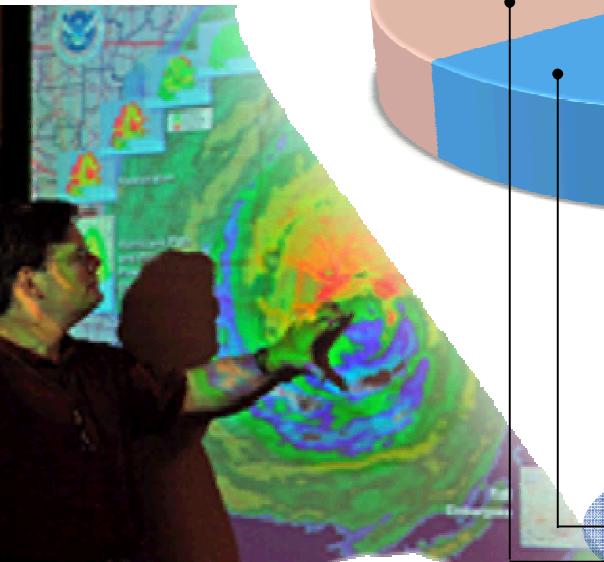
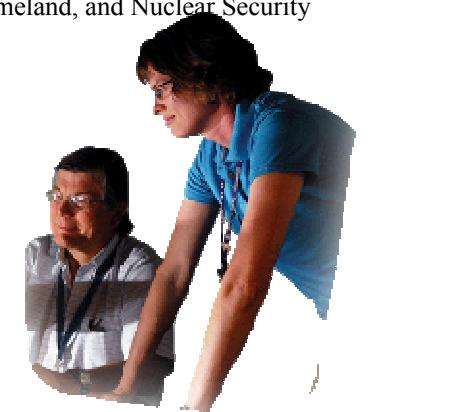


FY11 Operating Revenue
\$2.4 billion



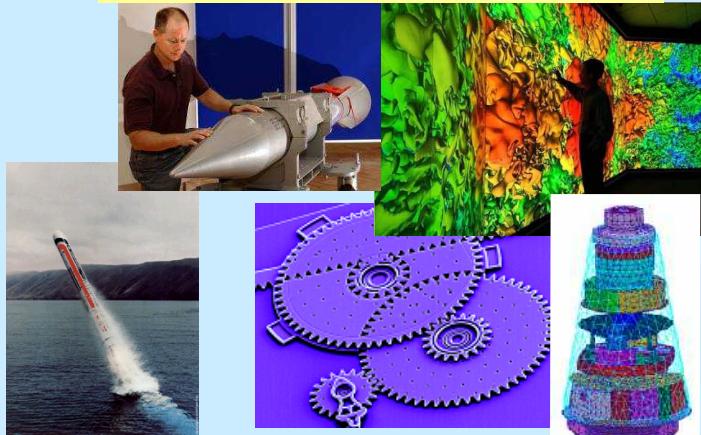
(Operating Budget)

- Nuclear Weapons
- Defense Systems & Assessments
- Energy, Climate & Infrastructure Security
- International, Homeland, and Nuclear Security



Sandia's Four Application Mission Areas (SMUs)

Nuclear Weapons



Defense Systems & Assessments



Energy, Climate, & Infrastructure



Homeland Security & Defense



ST&E Supports the Four Mission Areas

Nuclear Weapons



Defense Systems & Assessments



Science, Technology & Engineering



Energy, Climate & Infrastructure

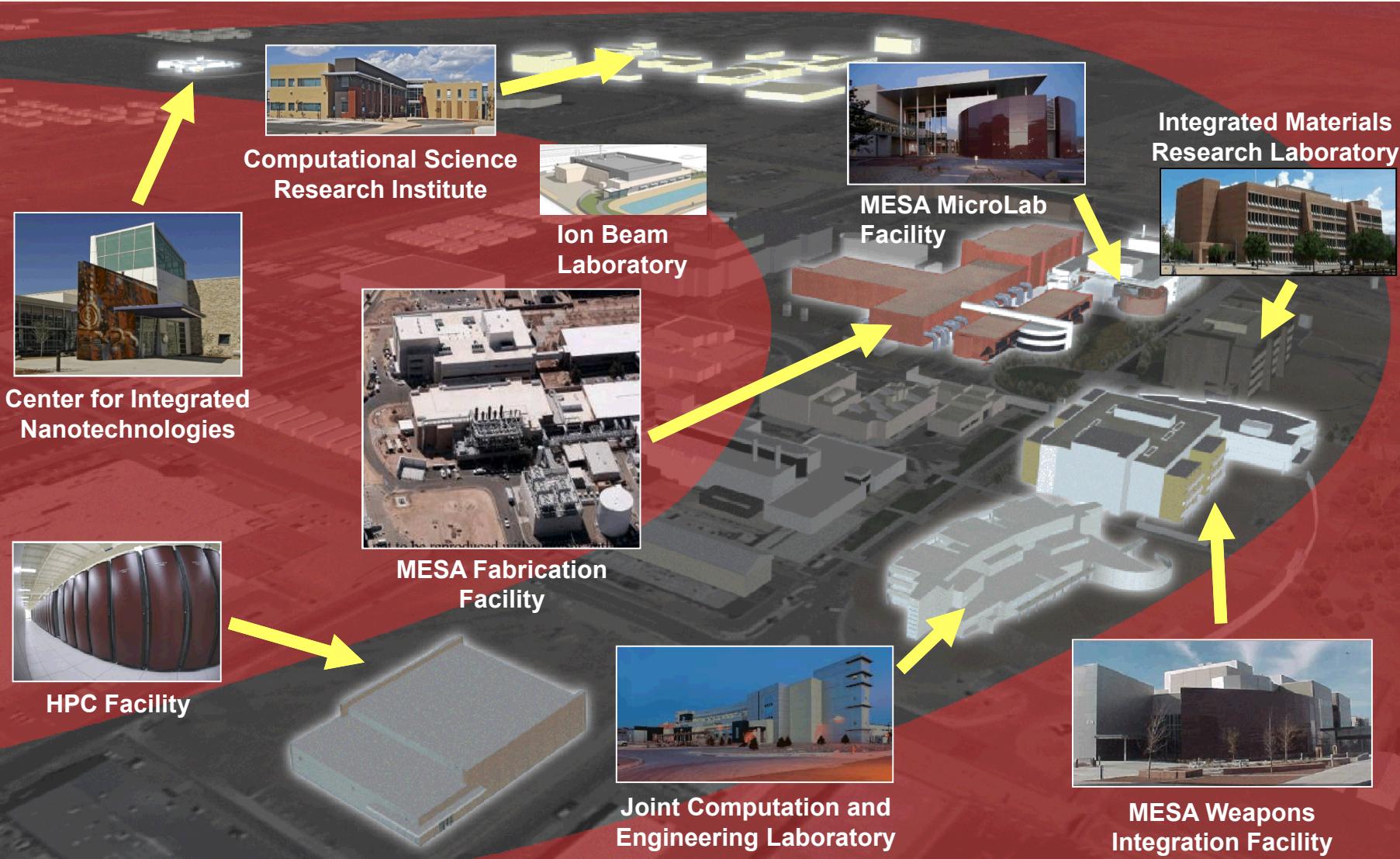


Health and Security & Response



ST&E is a fifth mission & SMU that supports the other four

Sandia's Innovation Corridor

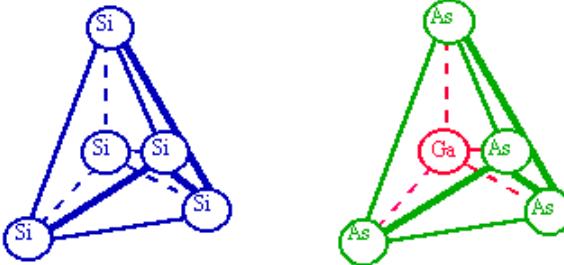


What are Semiconductors?

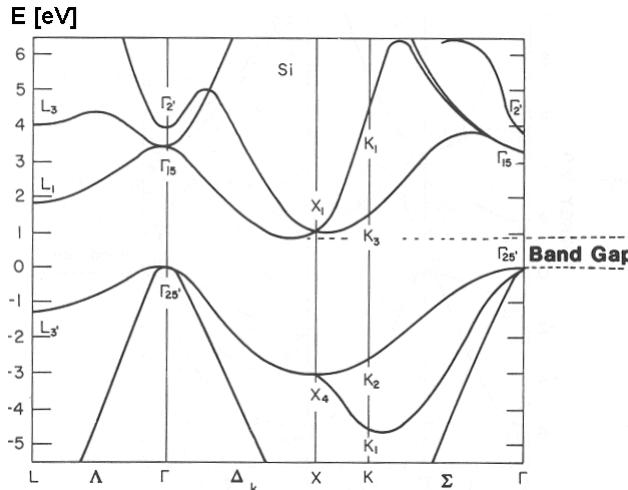
hydrogen 1 H 1.007	Group IV, III-V, II-VI																		helium 2 He 1.008																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																							
lithium 3 Li 6.941	boron 4 Be 9.012	silicon 14 Si 22.990	carbon 6 C 12	nitrogen 7 N 14.007	oxygen 8 O 16	fluorine 9 F 18.998	neon 10 Ne 20.180																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
sodium 11 Na 22.990	magnesium 12 Mg 24.305	phosphorus 15 P 30.974	aluminum 13 Al 26.982	silicon 14 Si 28.085	silicon 15 Si 32.075	chlorine 17 Cl 35.455	argon 18 Ar 39.948																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
potassium 19 K 39.098	calcium 20 Ca 40.078	iron 26 Fe 55.845	nickel 27 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.390	gallium 31 Ga 69.722	tin 32 Sn 74.922	tin 33 Sn 78.694	tin 34 Sn 79.904	tin 35 Sn 81.460	tin 36 Sn 83.655	tin 37 Sn 84.730	tin 38 Sn 85.440	tin 39 Sn 86.140	tin 40 Sn 86.840	tin 41 Sn 87.540	tin 42 Sn 88.240	tin 43 Sn 88.940	tin 44 Sn 89.640	tin 45 Sn 90.340	tin 46 Sn 91.040	tin 47 Sn 91.740	tin 48 Sn 92.440	tin 49 Sn 93.140	tin 50 Sn 93.840	tin 51 Sn 94.540	tin 52 Sn 95.240	tin 53 Sn 95.940	tin 54 Sn 96.640	tin 55 Sn 97.340	tin 56 Sn 98.040	tin 57 Sn 98.740	tin 58 Sn 99.440	tin 59 Sn 99.740	tin 60 Sn 99.940	tin 61 Sn 100.040	tin 62 Sn 100.340	tin 63 Sn 100.640	tin 64 Sn 100.940	tin 65 Sn 101.240	tin 66 Sn 101.540	tin 67 Sn 101.840	tin 68 Sn 102.140	tin 69 Sn 102.440	tin 70 Sn 102.740	tin 71 Sn 103.040	tin 72 Sn 103.340	tin 73 Sn 103.640	tin 74 Sn 103.940	tin 75 Sn 104.240	tin 76 Sn 104.540	tin 77 Sn 104.840	tin 78 Sn 105.140	tin 79 Sn 105.440	tin 80 Sn 105.740	tin 81 Sn 106.040	tin 82 Sn 106.340	tin 83 Sn 106.640	tin 84 Sn 106.940	tin 85 Sn 107.240	tin 86 Sn 107.540	tin 87 Sn 107.840	tin 88 Sn 108.140	tin 89 Sn 108.440	tin 90 Sn 108.740	tin 91 Sn 109.040	tin 92 Sn 109.340	tin 93 Sn 109.640	tin 94 Sn 109.940	tin 95 Sn 110.240	tin 96 Sn 110.540	tin 97 Sn 110.840	tin 98 Sn 111.140	tin 99 Sn 111.440	tin 100 Sn 111.740	tin 101 Sn 112.040	tin 102 Sn 112.340	tin 103 Sn 112.640	tin 104 Sn 112.940	tin 105 Sn 113.240	tin 106 Sn 113.540	tin 107 Sn 113.840	tin 108 Sn 114.140	tin 109 Sn 114.440	tin 110 Sn 114.740	tin 111 Sn 115.040	tin 112 Sn 115.340	tin 113 Sn 115.640	tin 114 Sn 115.940	tin 115 Sn 116.240	tin 116 Sn 116.540	tin 117 Sn 116.840	tin 118 Sn 117.140	tin 119 Sn 117.440	tin 120 Sn 117.740	tin 121 Sn 118.040	tin 122 Sn 118.340	tin 123 Sn 118.640	tin 124 Sn 118.940	tin 125 Sn 119.240	tin 126 Sn 119.540	tin 127 Sn 119.840	tin 128 Sn 120.140	tin 129 Sn 120.440	tin 130 Sn 120.740	tin 131 Sn 121.040	tin 132 Sn 121.340	tin 133 Sn 121.640	tin 134 Sn 121.940	tin 135 Sn 122.240	tin 136 Sn 122.540	tin 137 Sn 122.840	tin 138 Sn 123.140	tin 139 Sn 123.440	tin 140 Sn 123.740	tin 141 Sn 124.040	tin 142 Sn 124.340	tin 143 Sn 124.640	tin 144 Sn 124.940	tin 145 Sn 125.240	tin 146 Sn 125.540	tin 147 Sn 125.840	tin 148 Sn 126.140	tin 149 Sn 126.440	tin 150 Sn 126.740	tin 151 Sn 127.040	tin 152 Sn 127.340	tin 153 Sn 127.640	tin 154 Sn 127.940	tin 155 Sn 128.240	tin 156 Sn 128.540	tin 157 Sn 128.840	tin 158 Sn 129.140	tin 159 Sn 129.440	tin 160 Sn 129.740	tin 161 Sn 130.040	tin 162 Sn 130.340	tin 163 Sn 130.640	tin 164 Sn 130.940	tin 165 Sn 131.240	tin 166 Sn 131.540	tin 167 Sn 131.840	tin 168 Sn 132.140	tin 169 Sn 132.440	tin 170 Sn 132.740	tin 171 Sn 133.040	tin 172 Sn 133.340	tin 173 Sn 133.640	tin 174 Sn 133.940	tin 175 Sn 134.240	tin 176 Sn 134.540	tin 177 Sn 134.840	tin 178 Sn 135.140	tin 179 Sn 135.440	tin 180 Sn 135.740	tin 181 Sn 136.040	tin 182 Sn 136.340	tin 183 Sn 136.640	tin 184 Sn 136.940	tin 185 Sn 137.240	tin 186 Sn 137.540	tin 187 Sn 137.840	tin 188 Sn 138.140	tin 189 Sn 138.440	tin 190 Sn 138.740	tin 191 Sn 139.040	tin 192 Sn 139.340	tin 193 Sn 139.640	tin 194 Sn 139.940	tin 195 Sn 140.240	tin 196 Sn 140.540	tin 197 Sn 140.840	tin 198 Sn 141.140	tin 199 Sn 141.440	tin 200 Sn 141.740	tin 201 Sn 142.040	tin 202 Sn 142.340	tin 203 Sn 142.640	tin 204 Sn 142.940	tin 205 Sn 143.240	tin 206 Sn 143.540	tin 207 Sn 143.840	tin 208 Sn 144.140	tin 209 Sn 144.440	tin 210 Sn 144.740	tin 211 Sn 145.040	tin 212 Sn 145.340	tin 213 Sn 145.640	tin 214 Sn 145.940	tin 215 Sn 146.240	tin 216 Sn 146.540	tin 217 Sn 146.840	tin 218 Sn 147.140	tin 219 Sn 147.440	tin 220 Sn 147.740	tin 221 Sn 148.040	tin 222 Sn 148.340	tin 223 Sn 148.640	tin 224 Sn 148.940	tin 225 Sn 149.240	tin 226 Sn 149.540	tin 227 Sn 149.840	tin 228 Sn 150.140	tin 229 Sn 150.440	tin 230 Sn 150.740	tin 231 Sn 151.040	tin 232 Sn 151.340	tin 233 Sn 151.640	tin 234 Sn 151.940	tin 235 Sn 152.240	tin 236 Sn 152.540	tin 237 Sn 152.840	tin 238 Sn 153.140	tin 239 Sn 153.440	tin 240 Sn 153.740	tin 241 Sn 154.040	tin 242 Sn 154.340	tin 243 Sn 154.640	tin 244 Sn 154.940	tin 245 Sn 155.240	tin 246 Sn 155.540	tin 247 Sn 155.840	tin 248 Sn 156.140	tin 249 Sn 156.440	tin 250 Sn 156.740	tin 251 Sn 157.040	tin 252 Sn 157.340	tin 253 Sn 157.640	tin 254 Sn 157.940	tin 255 Sn 158.240	tin 256 Sn 158.540	tin 257 Sn 158.840	tin 258 Sn 159.140	tin 259 Sn 159.440	tin 260 Sn 159.740	tin 261 Sn 160.040	tin 262 Sn 160.340	tin 263 Sn 160.640	tin 264 Sn 160.940	tin 265 Sn 161.240	tin 266 Sn 161.540	tin 267 Sn 161.840	tin 268 Sn 162.140	tin 269 Sn 162.440	tin 270 Sn 162.740	tin 271 Sn 163.040	tin 272 Sn 163.340	tin 273 Sn 163.640	tin 274 Sn 163.940	tin 275 Sn 164.240	tin 276 Sn 164.540	tin 277 Sn 164.840	tin 278 Sn 165.140	tin 279 Sn 165.440	tin 280 Sn 165.740	tin 281 Sn 166.040	tin 282 Sn 166.340	tin 283 Sn 166.640	tin 284 Sn 166.940	tin 285 Sn 167.240	tin 286 Sn 167.540	tin 287 Sn 167.840	tin 288 Sn 168.140	tin 289 Sn 168.440	tin 290 Sn 168.740	tin 291 Sn 169.040	tin 292 Sn 169.340	tin 293 Sn 169.640	tin 294 Sn 169.940	tin 295 Sn 170.240	tin 296 Sn 170.540	tin 297 Sn 170.840	tin 298 Sn 171.140	tin 299 Sn 171.440	tin 300 Sn 171.740	tin 301 Sn 172.040	tin 302 Sn 172.340	tin 303 Sn 172.640	tin 304 Sn 172.940	tin 305 Sn 173.240	tin 306 Sn 173.540	tin 307 Sn 173.840	tin 308 Sn 174.140	tin 309 Sn 174.440	tin 310 Sn 174.740	tin 311 Sn 175.040	tin 312 Sn 175.340	tin 313 Sn 175.640	tin 314 Sn 175.940	tin 315 Sn 176.240	tin 316 Sn 176.540	tin 317 Sn 176.840	tin 318 Sn 177.140	tin 319 Sn 177.440	tin 320 Sn 177.740	tin 321 Sn 178.040	tin 322 Sn 178.340	tin 323 Sn 178.640	tin 324 Sn 178.940	tin 325 Sn 179.240	tin 326 Sn 179.540	tin 327 Sn 179.840	tin 328 Sn 180.140	tin 329 Sn 180.440	tin 330 Sn 180.740	tin 331 Sn 181.040	tin 332 Sn 181.340	tin 333 Sn 181.640	tin 334 Sn 181.940	tin 335 Sn 182.240	tin 336 Sn 182.540	tin 337 Sn 182.840	tin 338 Sn 183.140	tin 339 Sn 183.440	tin 340 Sn 183.740	tin 341 Sn 184.040	tin 342 Sn 184.340	tin 343 Sn 184.640	tin 344 Sn 184.940	tin 345 Sn 185.240	tin 346 Sn 185.540	tin 347 Sn 185.840	tin 348 Sn 186.140	tin 349 Sn 186.440	tin 350 Sn 186.740	tin 351 Sn 187.040	tin 352 Sn 187.340	tin 353 Sn 187.640	tin 354 Sn 187.940	tin 355 Sn 188.240	tin 356 Sn 188.540	tin 357 Sn 188.840	tin 358 Sn 189.140	tin 359 Sn 189.440	tin 360 Sn 189.740	tin 361 Sn 190.040	tin 362 Sn 190.340	tin 363 Sn 190.640	tin 364 Sn 190.940	tin 365 Sn 191.240	tin 366 Sn 191.540	tin 367 Sn 191.840	tin 368 Sn 192.140	tin 369 Sn 192.440	tin 370 Sn 192.740	tin 371 Sn 193.040	tin 372 Sn 193.340	tin 373 Sn 193.640	tin 374 Sn 193.940	tin 375 Sn 194.240	tin 376 Sn 194.540	tin 377 Sn 194.840	tin 378 Sn 195.140	tin 379 Sn 195.440	tin 380 Sn 195.740	tin 381 Sn 196.040	tin 382 Sn 196.340	tin 383 Sn 196.640	tin 384 Sn 196.940	tin 385 Sn 197.240	tin 386 Sn 197.540	tin 387 Sn 197.840	tin 388 Sn 198.140	tin 389 Sn 198.440	tin 390 Sn 198.740	tin 391 Sn 199.040	tin 392 Sn 199.340	tin 393 Sn 199.640	tin 394 Sn 199.940	tin 395 Sn 200.240	tin 396 Sn 200.540	tin 397 Sn 200.840	tin 398 Sn 201.140	tin 399 Sn 201.440	tin 400 Sn 201.740	tin 401 Sn 202.040	tin 402 Sn 202.340	tin 403 Sn 202.640	tin 404 Sn 202.940	tin 405 Sn 203.240	tin 406 Sn 203.540	tin 407 Sn 203.840	tin 408 Sn 204.140	tin 409 Sn 204.440	tin 410 Sn 204.740	tin 411 Sn 205.040	tin 412 Sn 205.340	tin 413 Sn 205.640	tin 414 Sn 205.940	tin 415 Sn 206.240	tin 416 Sn 206.540	tin 417 Sn 206.840	tin 418 Sn 207.140	tin 419 Sn 207.440	tin 420 Sn 207.740	tin 421 Sn 208.040	tin 422 Sn 208.340	tin 423 Sn 208.640	tin 424 Sn 208.940	tin 425 Sn 209.240	tin 426 Sn 209.540	tin 427 Sn 209.840	tin 428 Sn 210.140	tin 429 Sn 210.440	tin 430 Sn 210.740	tin 431 Sn 211.040	tin 432 Sn 211.340	tin 433 Sn 211.640	tin 434 Sn 211.940	tin 435 Sn 212.240	tin 436 Sn 212.540	tin 437 Sn 212.840	tin 438 Sn 213.140	tin 439 Sn 213.440	tin 440 Sn 213.740	tin 441 Sn 214.040	tin 442 Sn 214.340	tin 443 Sn 214.640	tin 444 Sn 214.940	tin 445 Sn 215.240	tin 446 Sn 215.540	tin 447 Sn 215.840	tin 448 Sn 216.140	tin 449 Sn 216.440	tin 450 Sn 216.740	tin 451 Sn 217.040	tin 452 Sn 217.340	tin 453 Sn 217.640	tin 454 Sn 217.940	tin 455 Sn 218.240	tin 456 Sn 218.540	tin 457 Sn 218.840	tin 458 Sn 219.140	tin 459 Sn 219.440	tin 460 Sn 219.740	tin 461 Sn 220.040	tin 462 Sn 220.340	tin 463 Sn 220.640	tin 464 Sn 220.940	tin 465 Sn 221.240	tin 466 Sn 221.540	tin 467 Sn 221.840	tin 468 Sn 222.140	tin 469 Sn 222.440	tin 470 Sn 222.740	tin 471 Sn 223.040	tin 472 Sn 223.340	tin 473 Sn 223.640	tin 474 Sn 223.940	tin 475 Sn 224.240	tin 476 Sn 224.540	tin 477 Sn 224.840	tin 478 Sn 225.140	tin 479 Sn 225.440	tin 480 Sn 225.740	tin 481 Sn 226.040	tin 482 Sn 226.340	tin 483 Sn 226.640	tin 484 Sn 226.940	tin 485 Sn 227.240	tin 486 Sn 227.540	tin 487 Sn 227.840	tin 488 Sn 228.140	tin 489 Sn 228.440	tin 490 Sn 228.740	tin 491 Sn 229.040	tin 492 Sn 229.340	tin 493 Sn 229.640	tin 494 Sn 229.940	tin 495 Sn 230.240	tin 496 Sn 230.540	tin 497 Sn 230.840	tin 498 Sn 231.140	tin 499 Sn 231.440	tin 500 Sn 231.740	tin 501 Sn 232.040	tin 502 Sn 232.340	tin 503 Sn 232.640	tin 504 Sn 232.940	tin 505 Sn 233.240	tin 506 Sn 233.540	tin 507 Sn 233.840	tin 508 Sn 234.140	tin 509 Sn 234.440	tin 510 Sn 234.740	tin 511 Sn 235.040	tin 512 Sn 235.340	tin 513 Sn 235.640	tin 514 Sn 235.940	tin 515 Sn 236.240	tin 516 Sn 236.540	tin 517 Sn 236.840	tin 518 Sn 237.140	tin 519 Sn 237.440	tin 520 Sn 237.740	tin 521 Sn 238.040	tin 522 Sn 238.340	tin 523 Sn 238.640	tin 524 Sn 238.940	tin 525 Sn 239.240	tin 526 Sn 239.540	tin 527 Sn 239.840	tin 528 Sn 240.140	tin 529 Sn 240.440	tin 530 Sn 240.740	tin 5

Group IV, III-V, II-VI

Tetrahedral bonding configuration

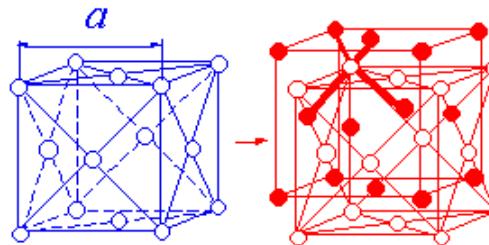


Face Centered Cubic and Diamond Crystal Structure



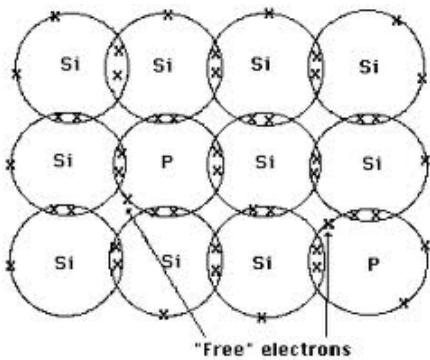
Bandstructure of Si

Google images

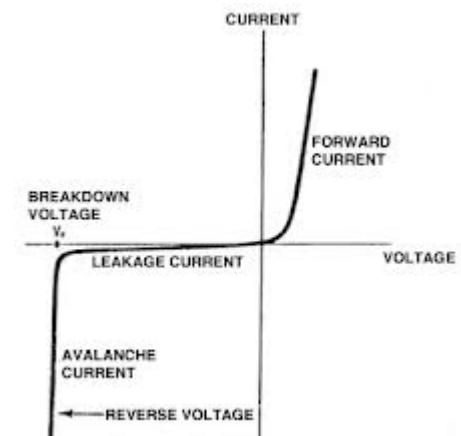
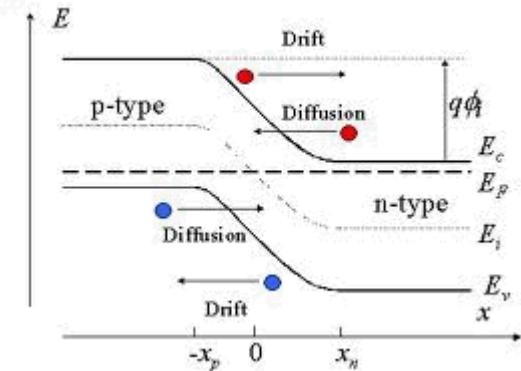
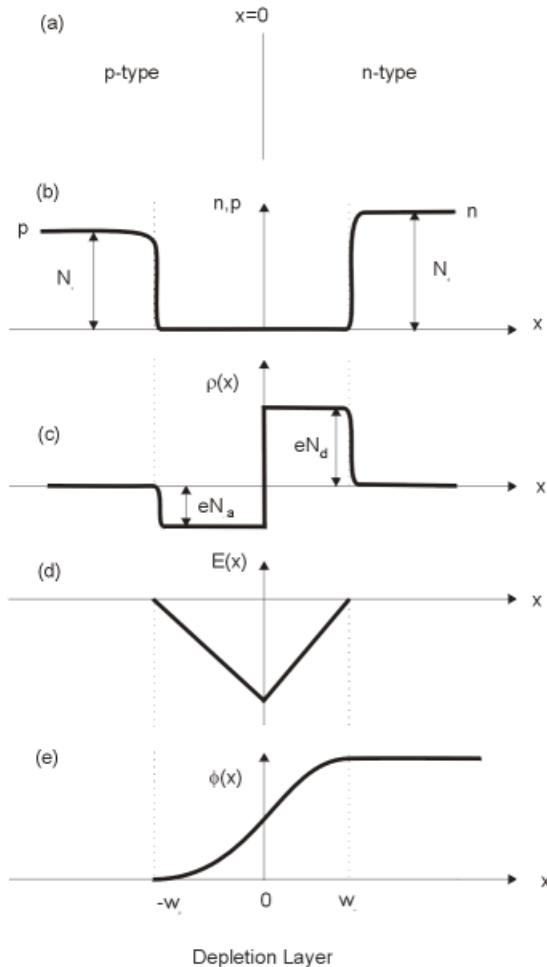


Diamond, Zincblende, or
Hexagonal (e.g. 2H, 4H, 6H)
crystal structure

Doping and pn Junctions



Doping of Si:
Extra electron = n-type
Missing electron = p-type

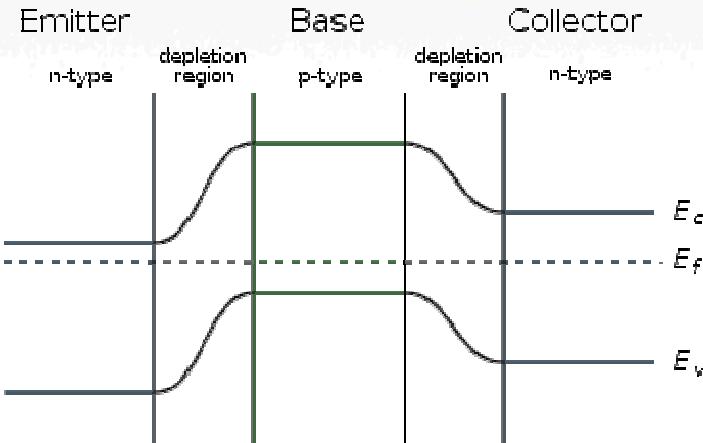


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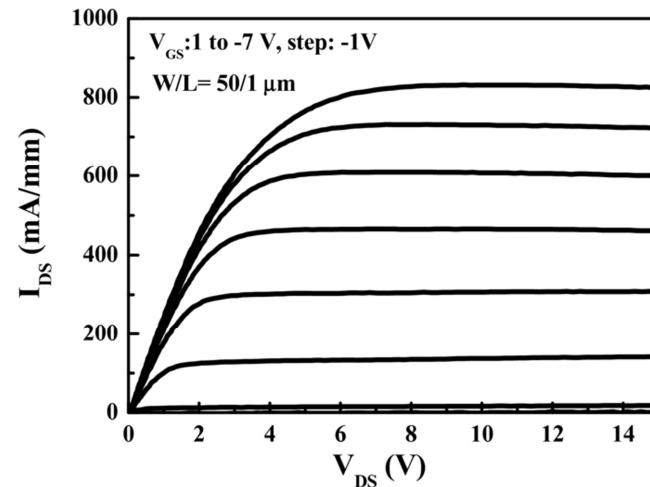
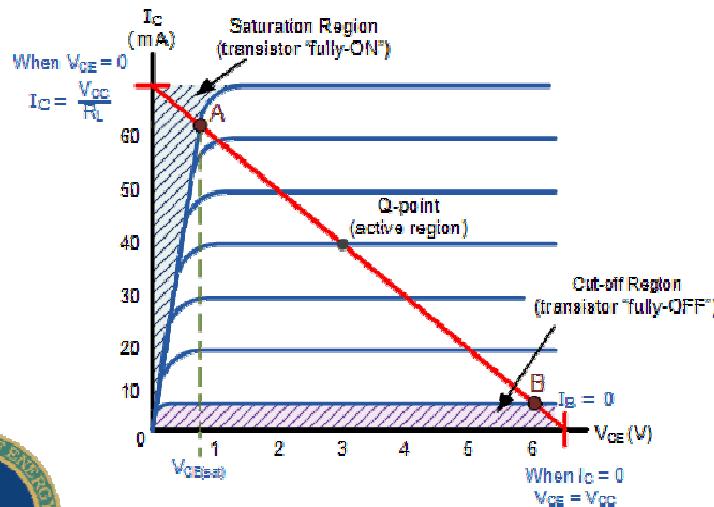
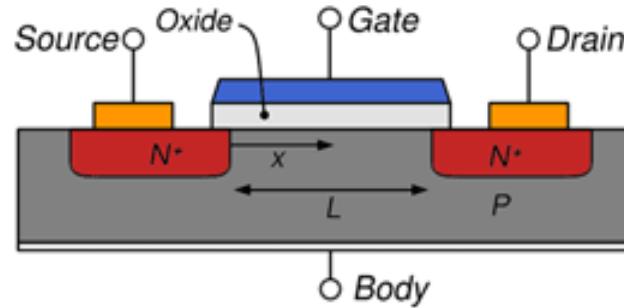


Bipolar and Field-Effect Transistors

Bipolar



Field-Effect



Google images



Comparison of Semiconductor Materials

WBG materials allow higher photon energy for optoelectronics, and higher voltage, current, temperature, and frequency for power electronics

Property	Si	4H-SiC	GaN	Diamond	AlN
Bandgap E_g , (eV)	1.1	3.2	3.4	5.5	6.2
Dielectric constant, ϵ_r	11.9	10.1	9	5.5	9
Electric breakdown field, E_c (MV/cm)	0.3	2.2	3	10	13
Electron Mobility, μ_n (cm ² /V·s)	1500	700	900 (bulk) 2000 (2D)	1900	300
Hole Mobility, μ_p (cm ² /V·s)	600	115	150	600	20
Thermal Conductivity, λ (W/cm·K)	1.5	4.9	> 1.3	22	2.9
Saturated Electron Drift Velocity, v_{sat} ($\times 10^7$ cm/s)	1	2	2.5	2.7	1.2



WBGs Are Increasingly Critical to Energy Technologies

Transitioning to cleaner and more efficient energy sources will require development and integration of WBG devices



Power electronics and inverters for electric vehicles and the electrical grid

Solid-state lighting

Material	Bandgap (eV)
Si	1.1
4H-SiC	3.2
GaN	3.4
Diamond	5.5
AlN	6.2

}

Wide-bandgap (WBG)

}

Ultra-wide-bandgap



WBGs Enable Reductions in Power Loss, Size, and Weight

Device	Brkdn Voltage	P _{switching} 500 Hz	P _{switching} 5 kHz	P _{switching} 20 kHz	P _{conduction} 100°C
Cree SiC MOSFET	12 kV	4 W/cm ²	40 W/cm ²	160 W/cm ²	100 W/cm ²
ABB Si IGBT	2x6.5 kV	72.5 W/cm ²	725 W/cm ²	2900 W/cm ²	182 W/cm ²

SiC MOSFET module
10 kV, 120 A

SiC MOSFET module is 10% weight and 12% volume of Si IGBT module

Cree/Powerex/GE

Si IGBT module
13.5 kV, 100 A

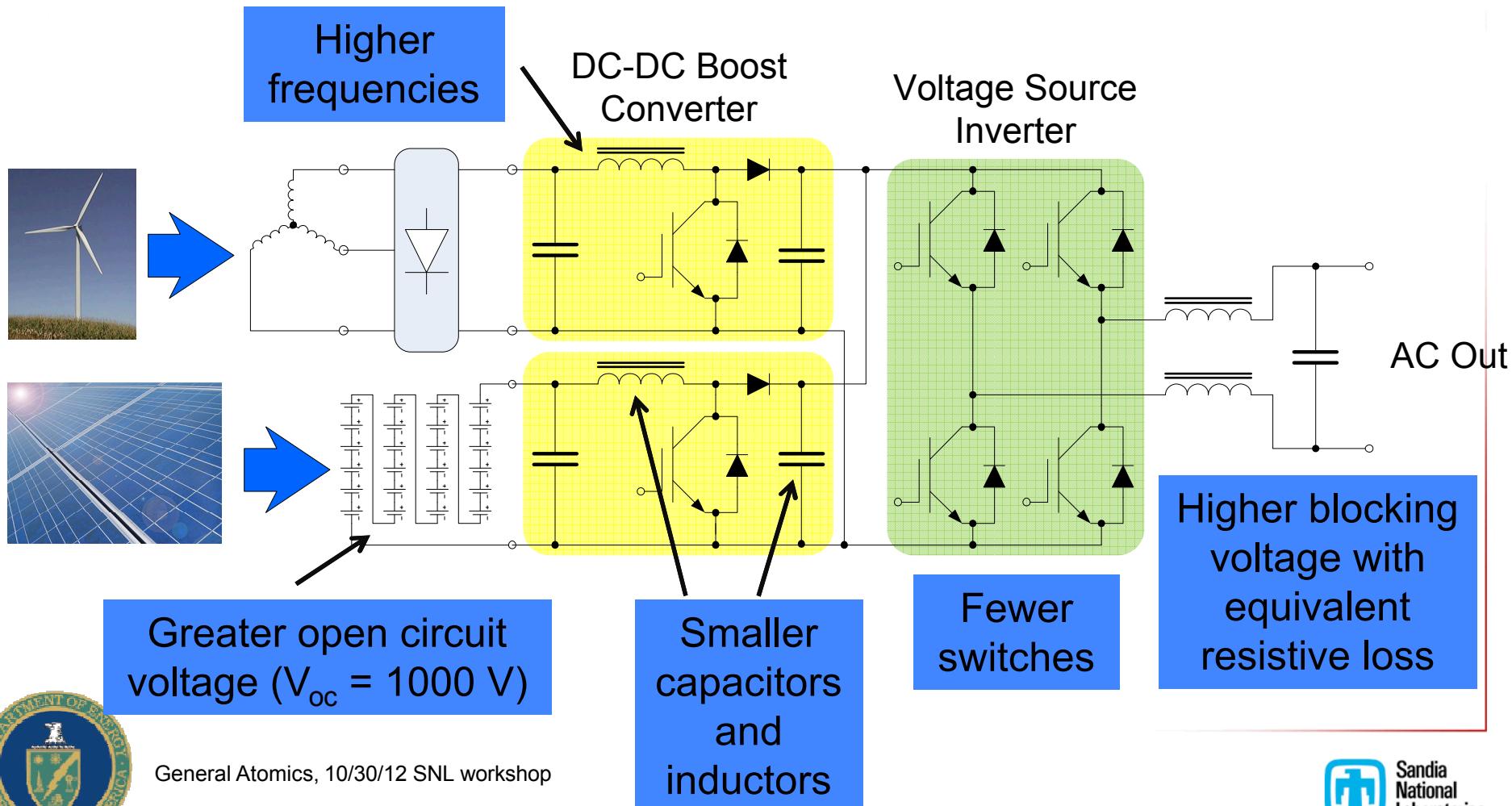


M. K. Das et al., ICSCRM 2011



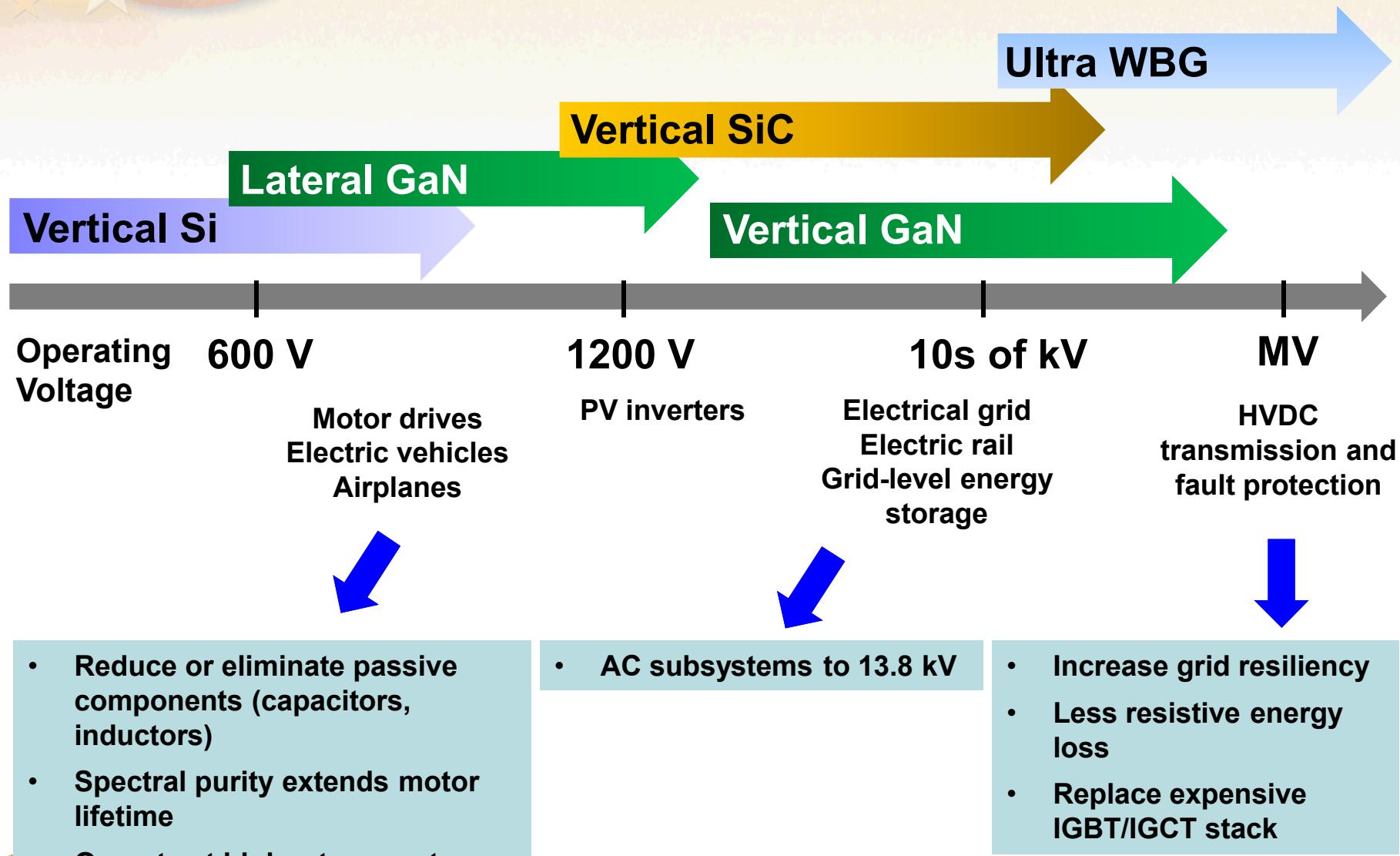
WBGs for Increased Grid Efficiency and Resiliency

A modern, resilient electric grid with integrated renewable power sources requires power electronics and power inverters



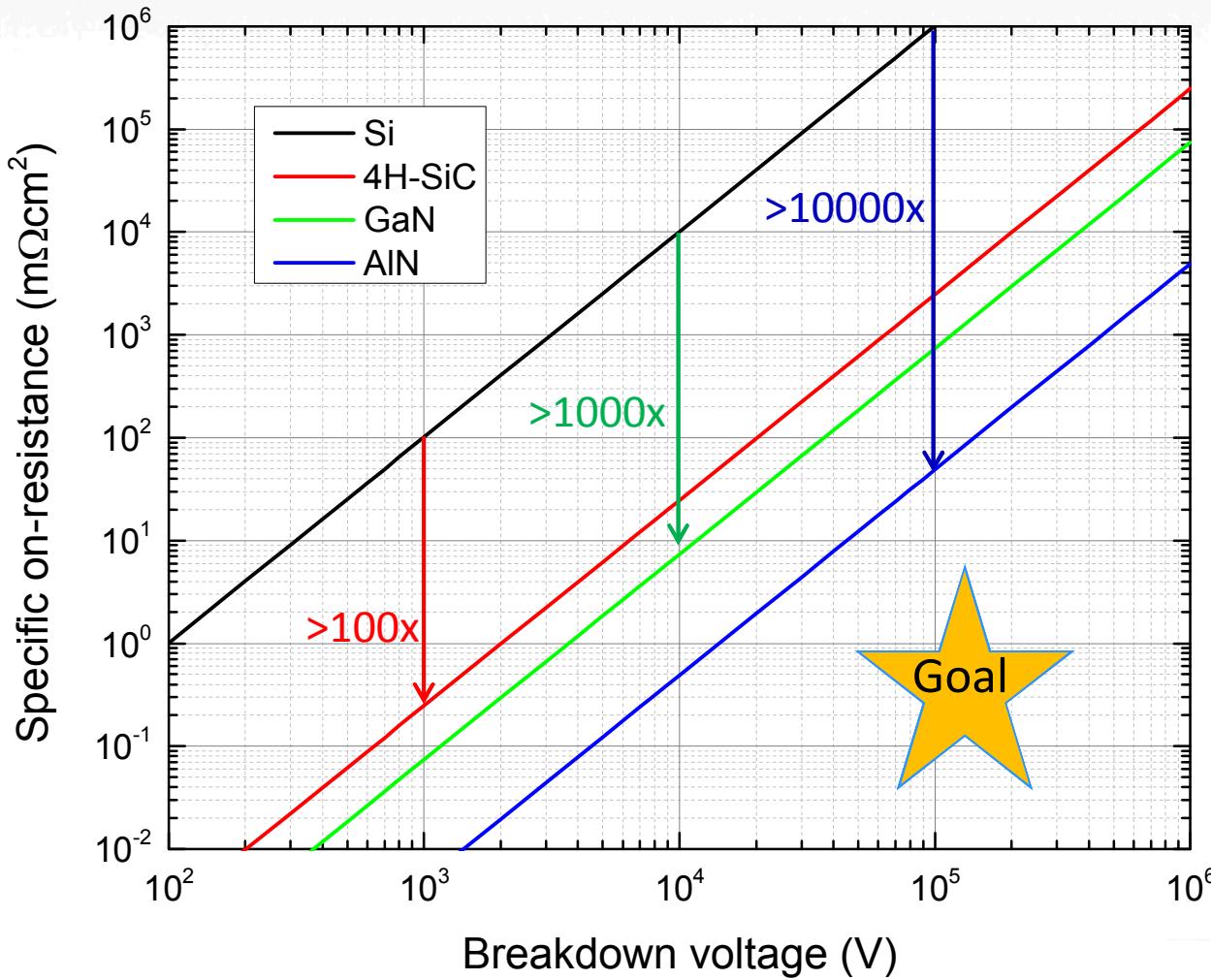
General Atomics, 10/30/12 SNL workshop

Application Space for WBG Devices

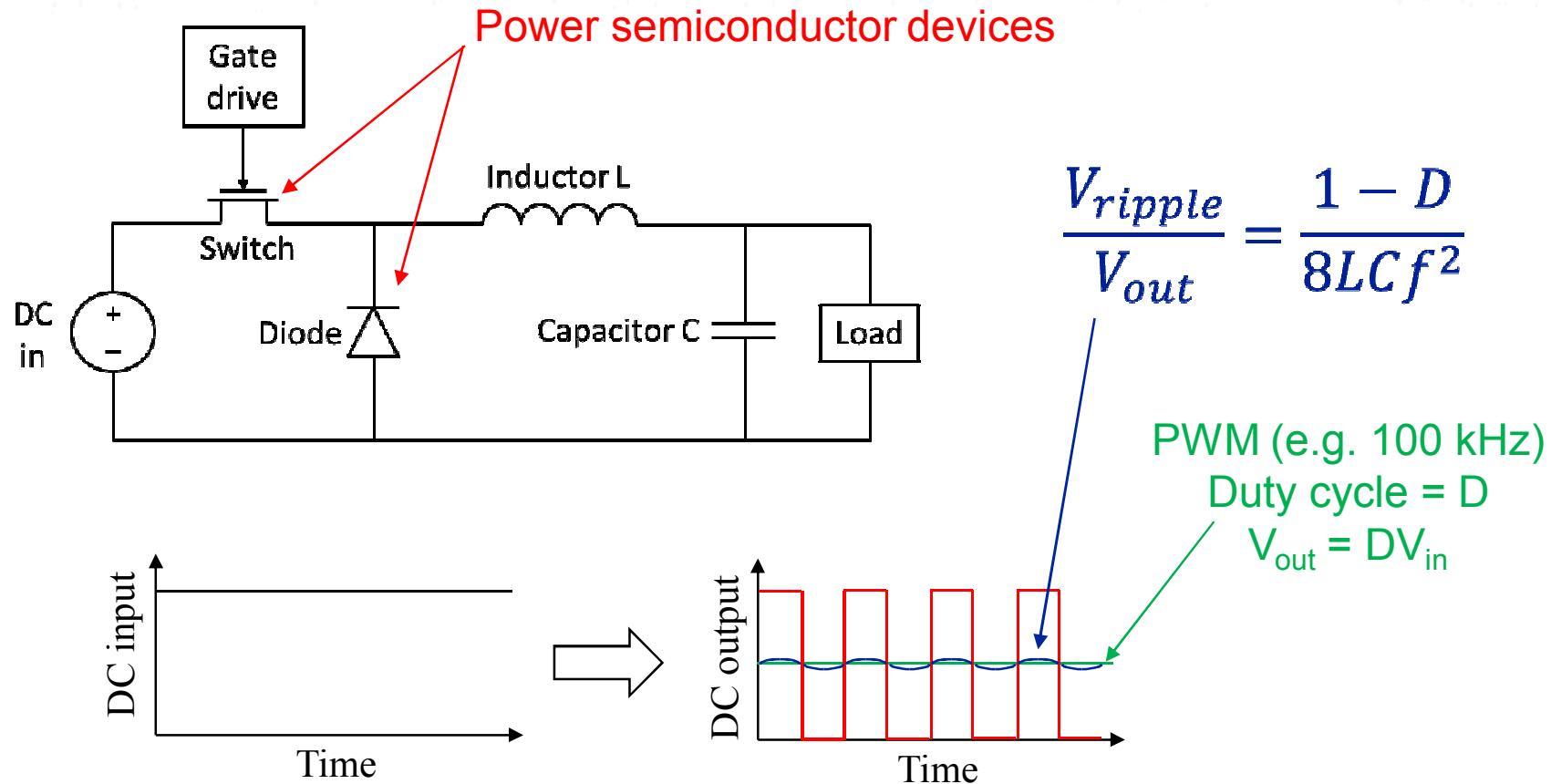


WBGs Offer Orders-of-Magnitude Improvement for PE

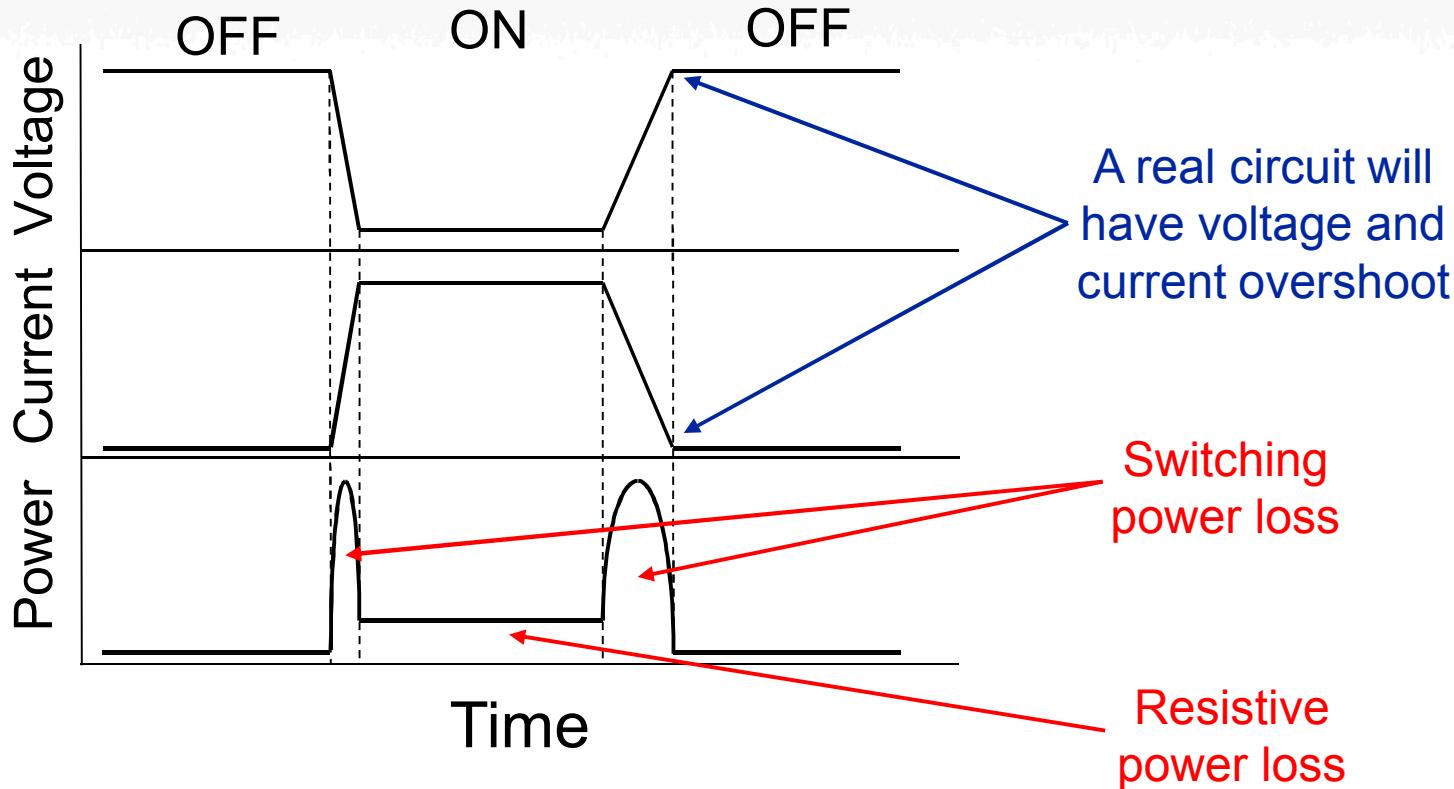
Unipolar Figure-of-Merit for Various Materials



Example Power Electronics Circuit: Step-Down (Buck) DC-to-DC Converter



PE Switch Current, Voltage, and Power Waveforms



Minimum ON-state loss: Low R_{on}

Minimum OFF-state loss: Low leakage

Minimum switching loss: Fast switching transients



Application Classes of Power Devices

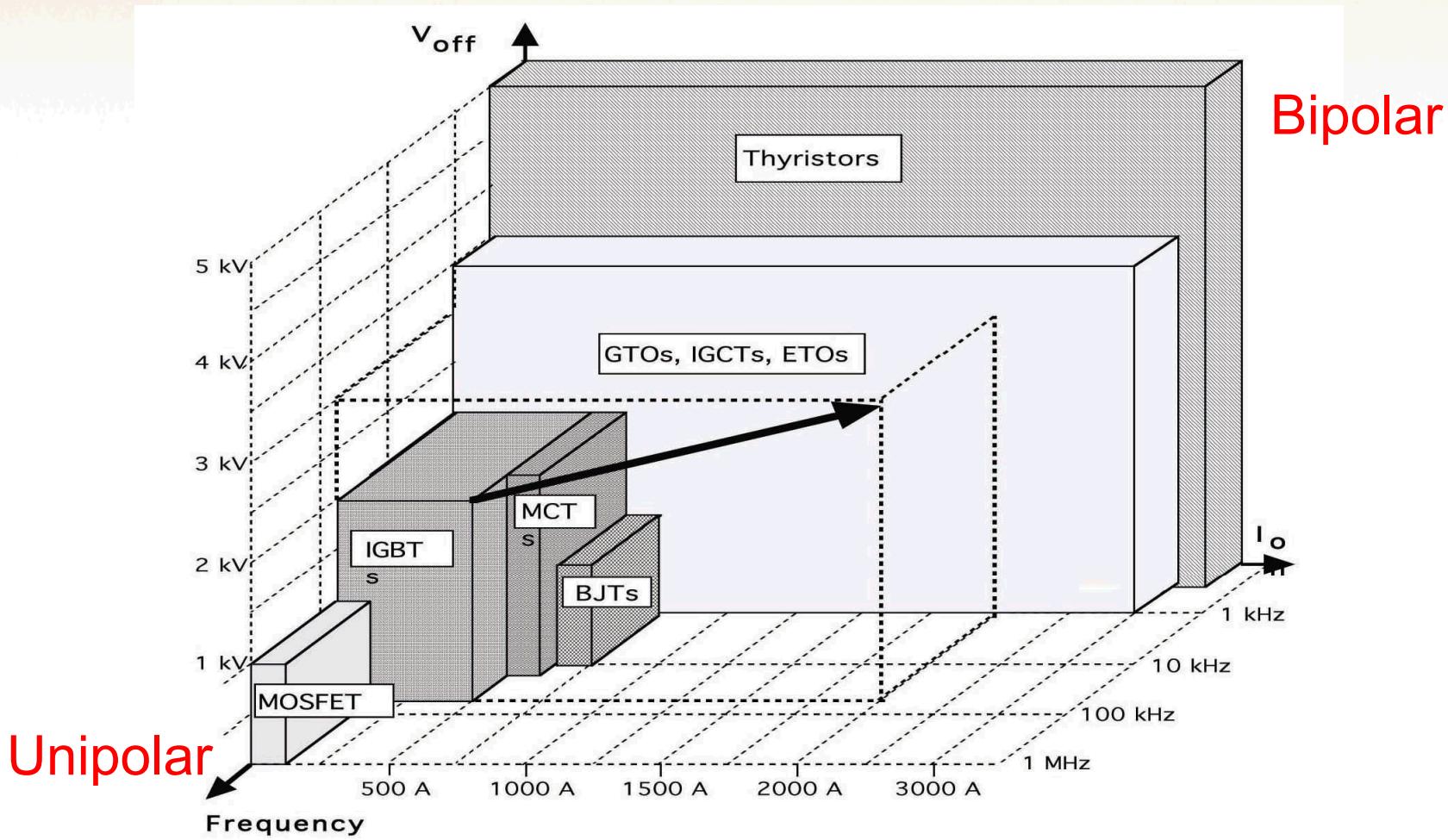
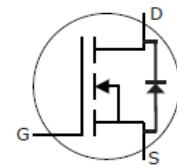
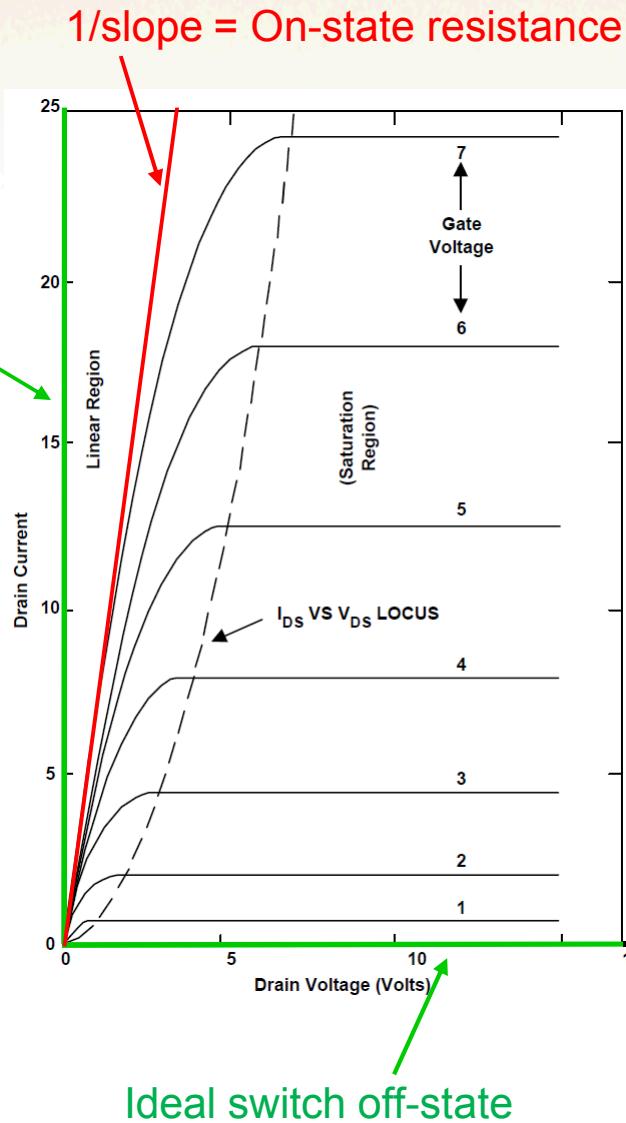


Figure from Mohan et al., "Power electronics: Converters, Applications, and Design" (Wiley, 2003).



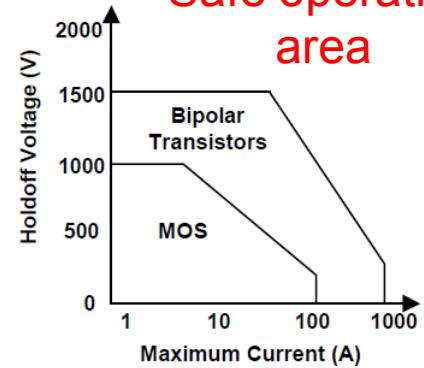
Real Power Devices are NOT Ideal Switches!

Ideal switch on-state



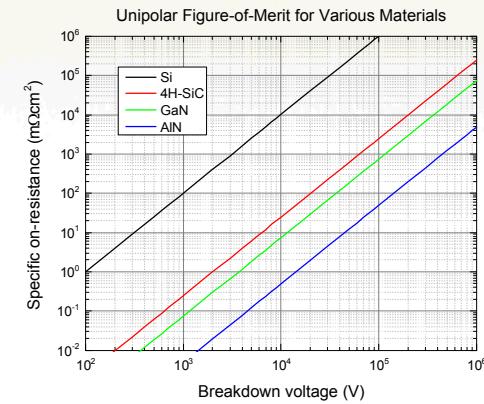
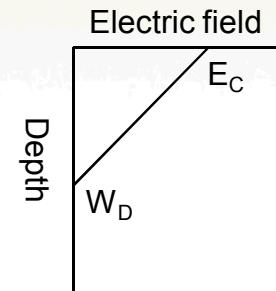
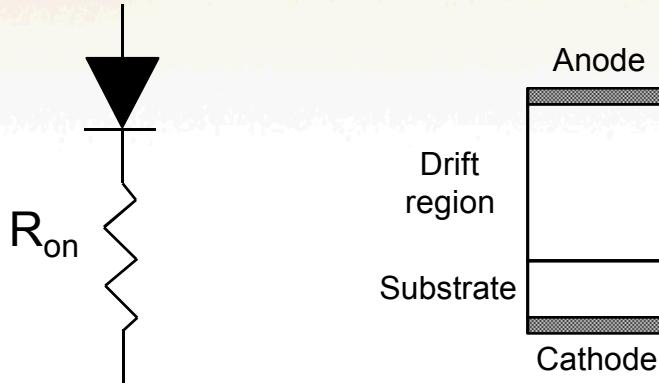
e.g. ≈ 1200 V

Safe operating area



Avalanche breakdown

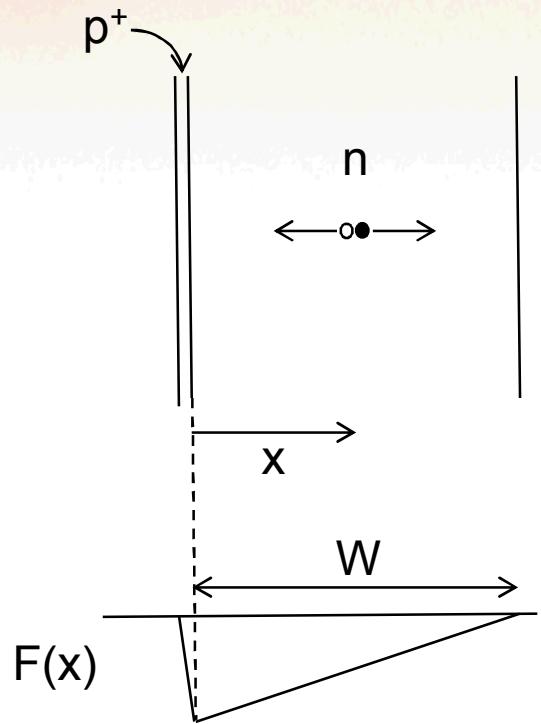
Unipolar Power Device Figure-of-Merit



- Off-state: Integrate electric field to get breakdown voltage $V_B = W_D E_C / 2$ (1)
- Gauss' law: $\epsilon E_C = q N_D W_D$ (2)
- On-state: Current transport due to carrier drift, resistance $R_{on} = W_D / sA$
Conductivity $\sigma = q \mu_n n = q \mu_n N_D$ assuming complete dopant ionization
Specific on-resistance $R_{on,sp} = R_{on} A = W_D / \sigma = W_D / q \mu_n N_D$ (3)
- Combining (1) and (2) gives dependence of V_B on N_D and E_C : $V_B = \epsilon E_C^2 / 2qN_D$
- Combining (1), (2), and (3) one obtains the unipolar “figure-of-merit”:
 $R_{on,sp} = 4V_B^2 / \epsilon \mu_n E_C^3$



Avalanche Breakdown Physics: Impact Ionization in a Depletion Region



Impact ionization coefficient for electrons, holes = α_n , α_p = # of ehtps generated per cm by an incident hot electron, hole; may be defined in terms of generation rate:

$$G_{ii} = \alpha_n J_n + \alpha_p J_p$$

α_n and α_p are strong functions of electric field!

Suppose that an electron-hole pair is generated at position x. Then the number of ehtps $N(x)$ generated at position x is (1):

$$N(x) = 1 + \int_0^x \alpha_p N(x') dx' + \int_x^W \alpha_n N(x') dx'$$

This can be differentiated to give:

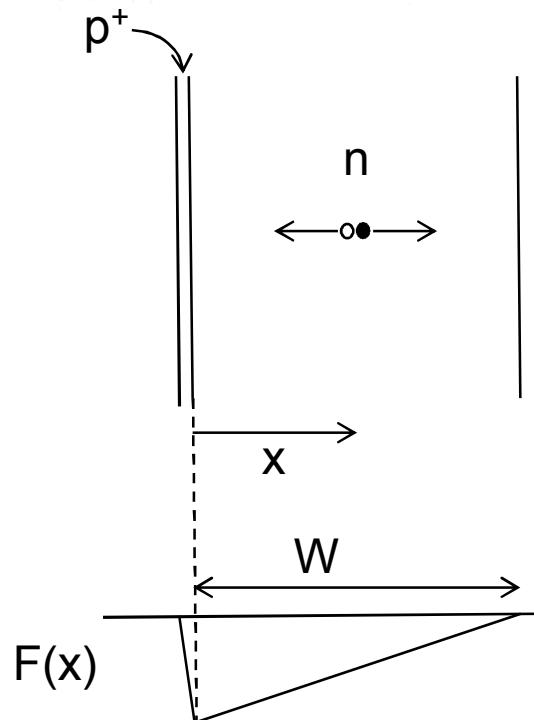
$$\frac{dN}{dx} = (\alpha_p - \alpha_n)N(x)$$

The solution of the differential equation is:

$$N(x) = N(0) \exp \left[\int_0^x (\alpha_p - \alpha_n) dx' \right]$$

Criterion for Avalanche Breakdown

The equations may be combined to give (after some algebra):



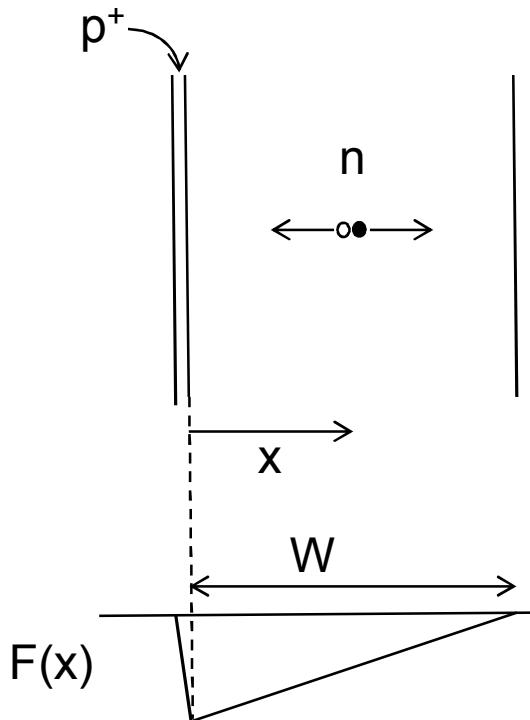
$$N(x) = \frac{\exp\left[\int_0^x (\alpha_p - \alpha_n) dx'\right]}{1 - \int_0^W \alpha_n \exp\left[\int_0^x (\alpha_p - \alpha_n) dx'\right] dx}$$

Avalanche breakdown occurs when the number of generated ehps tends to infinity, i.e. when the denominator goes to zero:

$$\int_0^W \alpha_n \exp\left[\int_0^x (\alpha_p - \alpha_n) dx'\right] dx = 1$$

Since α_n and α_p are such strong functions of electric field, in practice this always occurs near the location of peak field, and the majority of the contribution to the integral is from a small volume near this point (i.e. at the junction).

Approximations for Analytical Solutions



The approximation that α_n and α_p are proportional is often used:

$\alpha_p = \gamma \alpha_n$ in which case the ionization integral reduces to:

$$\int_0^W \frac{\alpha_p - \alpha_n}{\ln(\alpha_p/\alpha_n)} dx = \int_0^W \alpha_{eff} dx = 1$$

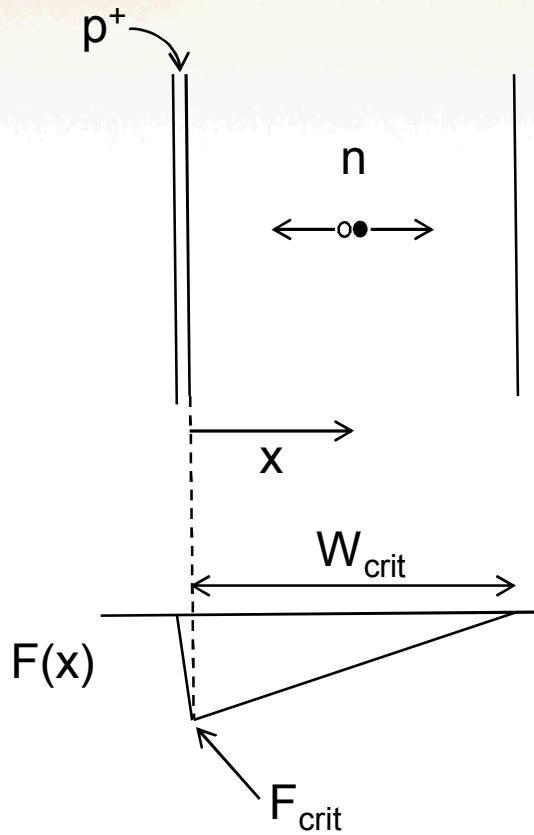
The “effective” impact ionization rate is often empirically modeled as $\alpha_{eff} = \alpha_{eff,0} F^7$

Finally, for a uniformly doped single-sided pn junction, the electric field is given by:

$$F(x) = -\frac{qN_D W}{\epsilon} \left(1 - \frac{x}{W}\right)$$

The last expression is important for the definition of the “critical field”.

What is the “Critical Field”?



Critical fields for:
Si: 0.2 MV/cm
4H-SiC: 2 MV/cm
GaN: 3 MV/cm

The critical field is defined as the maximum magnitude electric field in a uniformly doped, one-sided pn junction at the point when avalanche breakdown is initiated:

$$\int_0^W \alpha_{eff} \left[F_{crit} \left(1 - \frac{x}{W_{crit}} \right) \right] dx \approx \int_0^W \alpha_{eff,0} F_{crit}^7 \left(1 - \frac{x}{W_{crit}} \right)^7 dx = 1$$

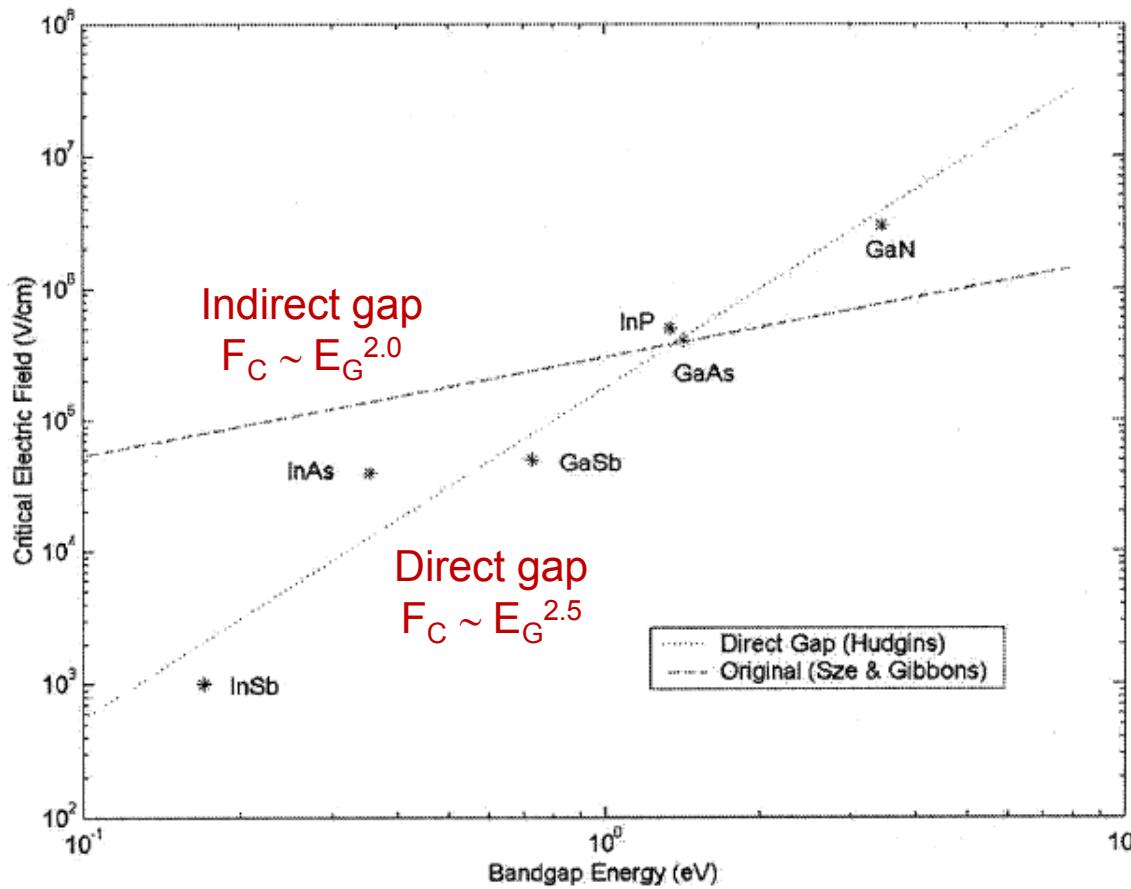
$$\text{with } F_{crit} = qN_D W_{crit} / \epsilon$$

Performing the integral gives:

$$F_{crit} = (8qN_D / \alpha_{eff,0} \epsilon)^{1/8}$$

Note that this is doping-dependent, but this is a weak dependence (and highly approximate) and in practice F_{crit} is taken to be constant.

Dependence of Critical Field on Bandgap



J. L. Hudgins, G. S. Simin, E. Santi, and M. A. Khan, "An Assessment of Wide Bandgap Semiconductors for Power Devices," IEEE Trans. on Elect. Dev. **18**(3), 907 (2003).

Analytical Models for Impact Ionization Coefficients

The most widely used model for impact ionization by device engineers is due to Shockley (1), and is based on the “lucky electron” idea in which electron avoid scattering events until the threshold energy is attained. This results in:

$$\alpha_{n,p}(F) = a_{n,p} \exp(-b_{n,p}/F)$$

An alternative theory was proposed by Wolff (2) in which impact ionization occurs due to carriers in the high-energy tail (above E_{th}) of a shifted Maxwellian distribution (electrons undergo numerous collisions, which is essentially the opposite view of Shockley):

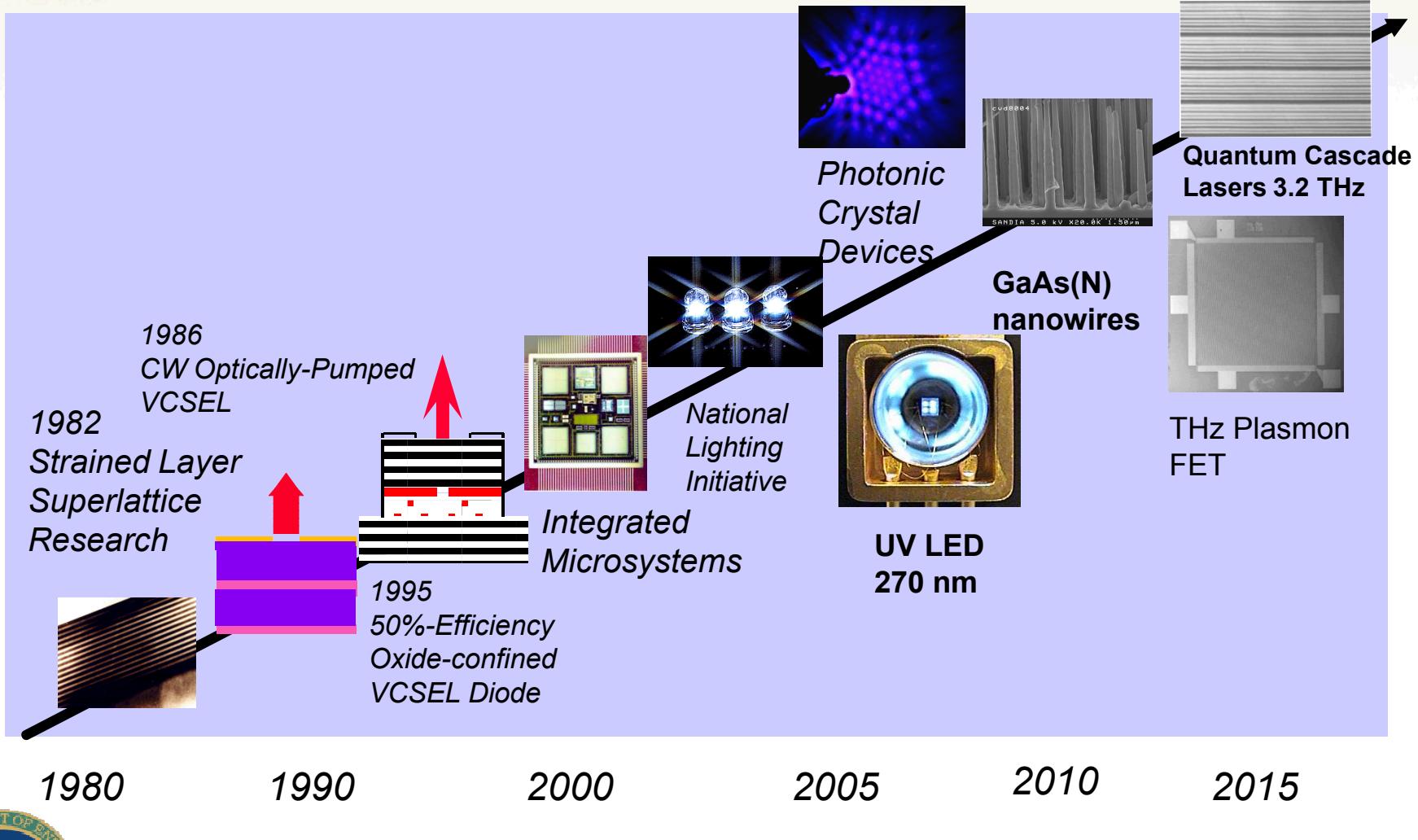
$$\alpha_{n,p}(F) = a_{n,p} \exp(-b_{n,p}/F^2)$$

Numerous other papers (e.g. 3, 4) have been published expanding upon these theories. However, in practice the Shockley expression dominates the power electronics world. ***Is this expression appropriate for WBG semiconductors?***

- 1.) W. Shockley, “Problems Related to pn Junctions in Silicon,” *Solid-State Electronics* **2**, 35 (1961).
- 2.) P. A. Wolff, “Theory of Electron Multiplication in Silicon and Germanium,” *Phys. Rev.* **95**, 1415 (1954).
- 3.) G. M. Baraff, “Distribution functions and Ionization Rates for Hot Electrons in Semiconductors,” *Phys. Rev.* **128**, 2507 (1962).
- 4.) H. Shichijo and K. Hess, “Band-Structure Dependent Transport and Impact Ionization in GaAs,” *Phys. Rev. B* **23**, 4197 (1981).

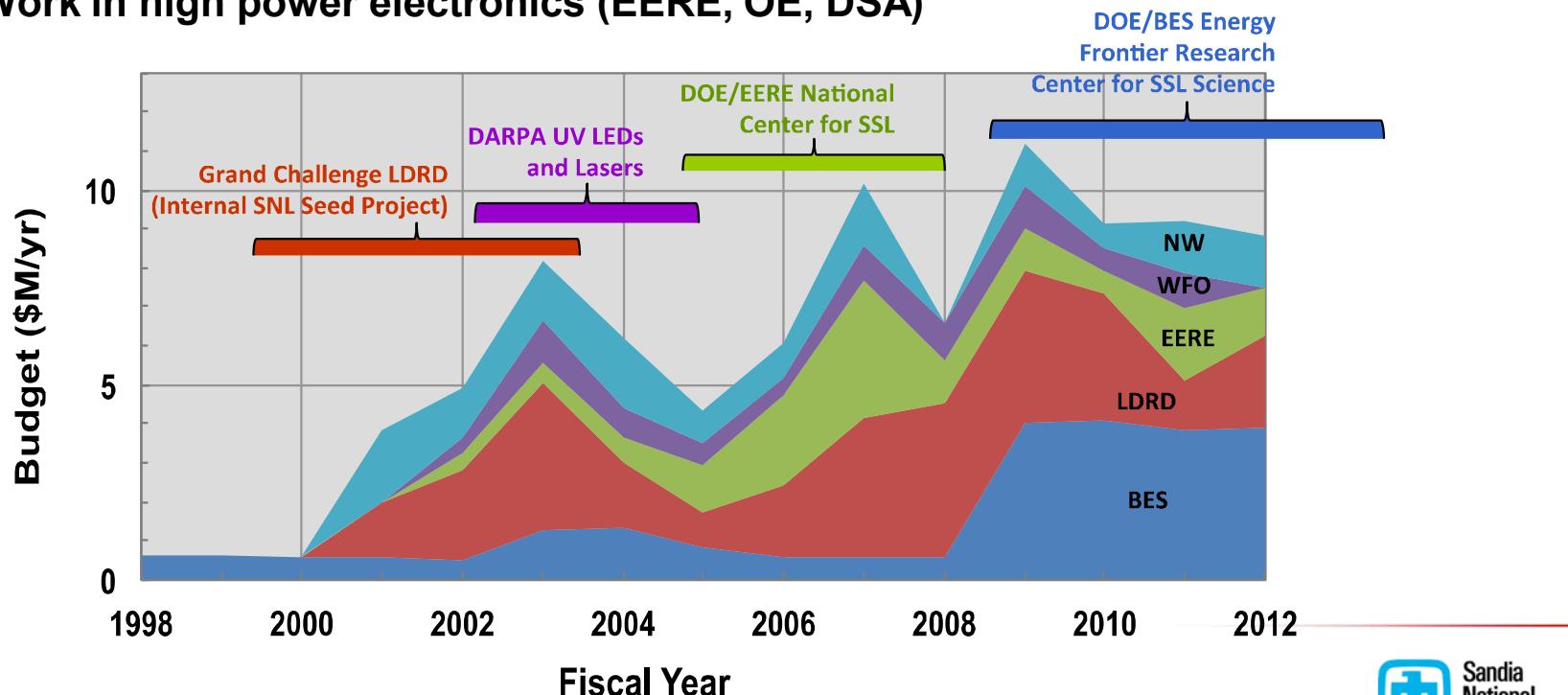


SNL 1980-2012: 30+ Years of Compound Semiconductor S&T



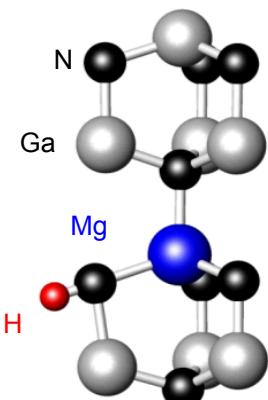
Significant Ongoing Activity in Wide Bandgaps

- 40-year history of, and recognized complex-wide as leader in, semiconductor materials and device R&D
- Strong culture of collaboration with industry
- 15 years of pioneering GaN-based materials and devices
 - SSL: Wide recognition of SNL as lead DOE lab; \$18M EFRC (SC, EERE)
 - Work in UV optoelectronics (NW, DSA)
 - Work in high power electronics (EERE, OE, DSA)



2009 – Present: Energy Frontier Research Center for SSL Science

Chemical Vapor Deposition Sciences

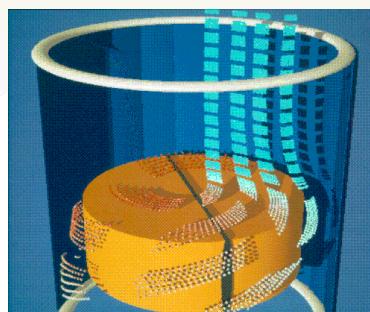
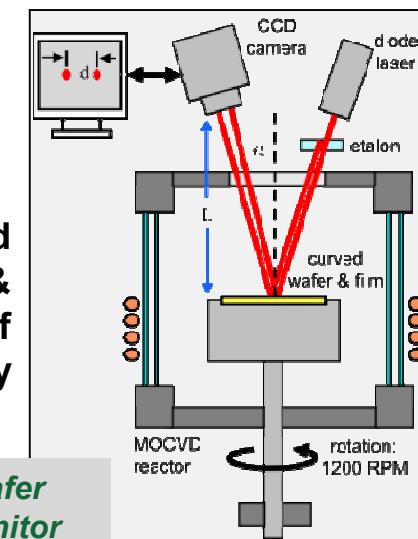


Defects in GaN Semiconductors

DFT calculations of defect energies

Advanced Growth & Science of Epitaxy

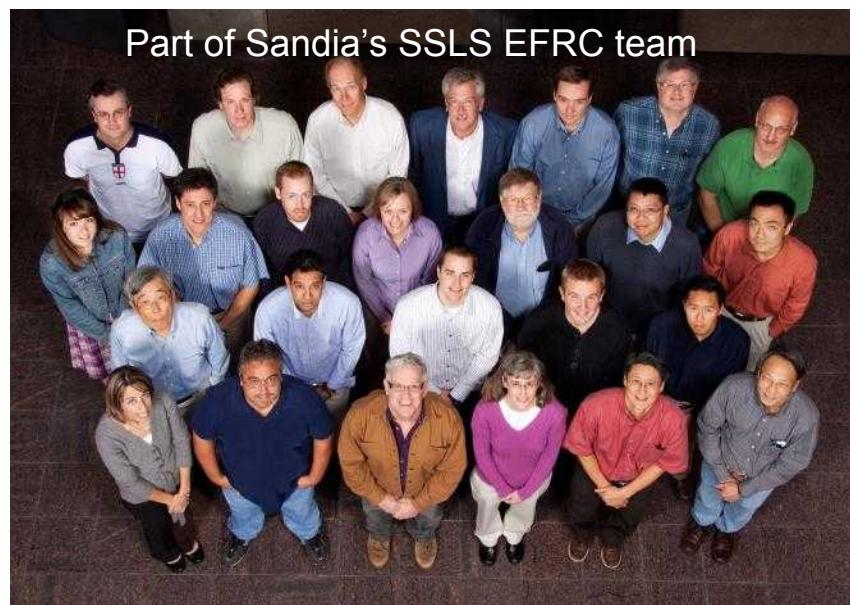
In-situ wafer stress monitor



Modeling of chemically reacting reactor flows



Part of Sandia's SSLS EFRC team



THE UNIVERSITY of
NEW MEXICO



Los Alamos
NATIONAL LABORATORY

PHILIPS



Yale
UNIVERSITY

WBG PE Under Sandia's Energy Storage Program

Funded by DOE Energy Storage Program (Dr. Imre Gyuk)
Sandia's Energy Storage PE Program led by Dr. Stan Atcitty

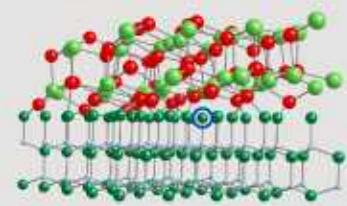
Materials R&D

Semiconductor devices

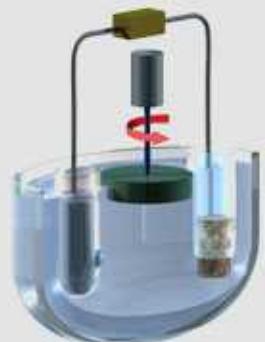
Power Modules

Power Conversion System

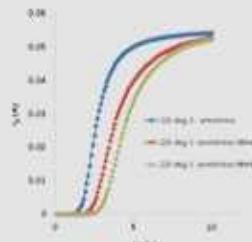
Applications



- Gate Oxide R&D
- Bulk GaN



- Post Si Characterization & Reliability
- SiC Thyristors
- ETO



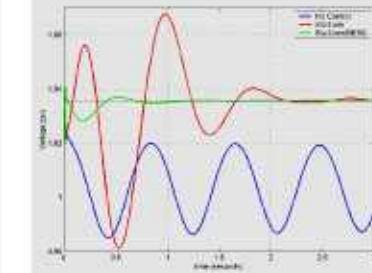
Power Modules



- High Temp/density Power Module



- Dstatcom plus energy storage for wind energy
- Optically isolated MW Inverter
- High density inverter with integrated thermal management
- High temp power inverter



- Power smoothing and control for renewables
- FACTS and Energy Storage

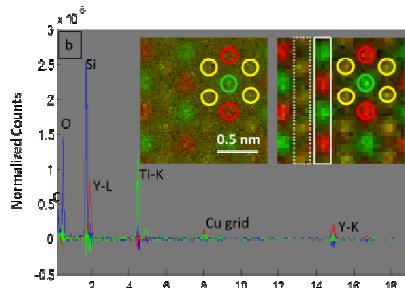


SNL has Extensive R&D Capabilities in Wide Bandgaps – Materials, Devices, and Systems

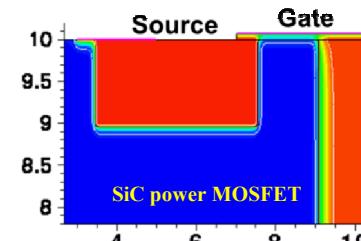
- 60+ years as DOE/NNSA mission lead in electronics
- 30+ years of compound semiconductor research
- 20+ years of wide band gap materials & device R&D
- **Facilities:** ~30,000 ft² clean room (MESA facility); Solid-State Lighting EFRC; microgrid testbed (DETL facility); ASIC design & fab; extensive reliability testing and failure analysis



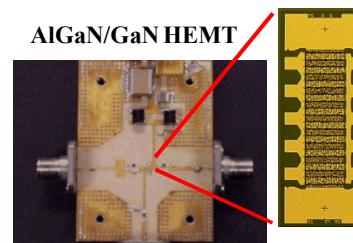
Atomic scale



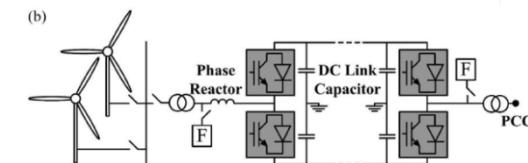
Atomic-resolution characterization



Material and device simulation



Device fabrication (MESA fab)

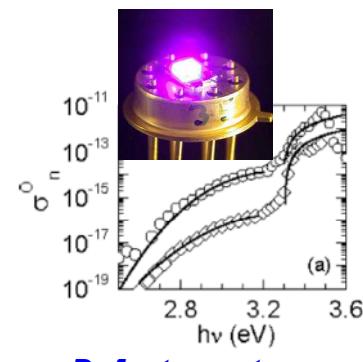


Power circuits and systems

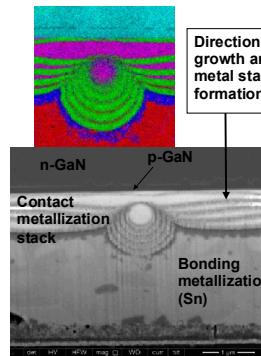
Grid scale



Epitaxial growth



Defect spectroscopy



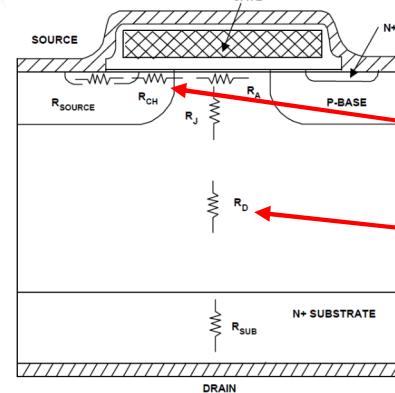
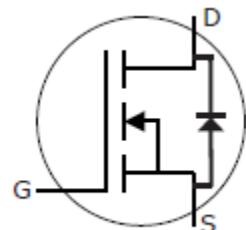
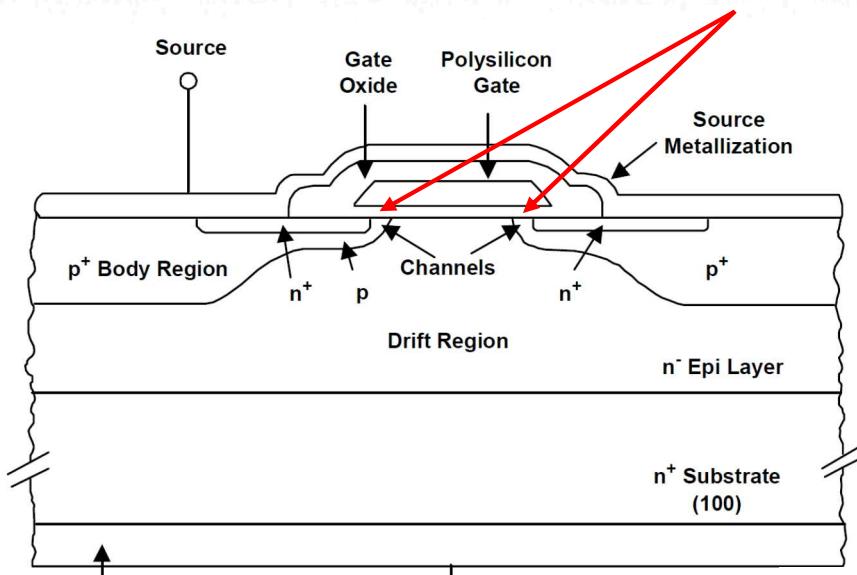
Reliability physics



Grid-level power networks (DETL)

WBG Research at Sandia: SiC Power MOSFET Reliability

Critical gate oxide interfacial region



Channel resistance can dominate drift region resistance

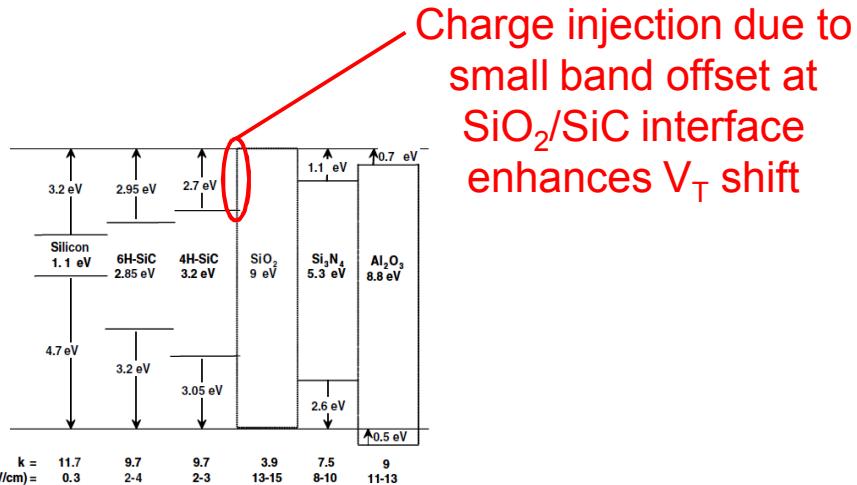


Fig. 1. Dielectric constants, and critical electric fields of various semiconductors (Si, 6H-SiC, 4H-SiC) and dielectrics (SiO₂, Si₃N₄ and Al₂O₃). Conduction and valence band offsets of these are also shown with respect to SiO₂.

R. Singh, Microelectronics Reliability, v. 46, p. 713 (2006).

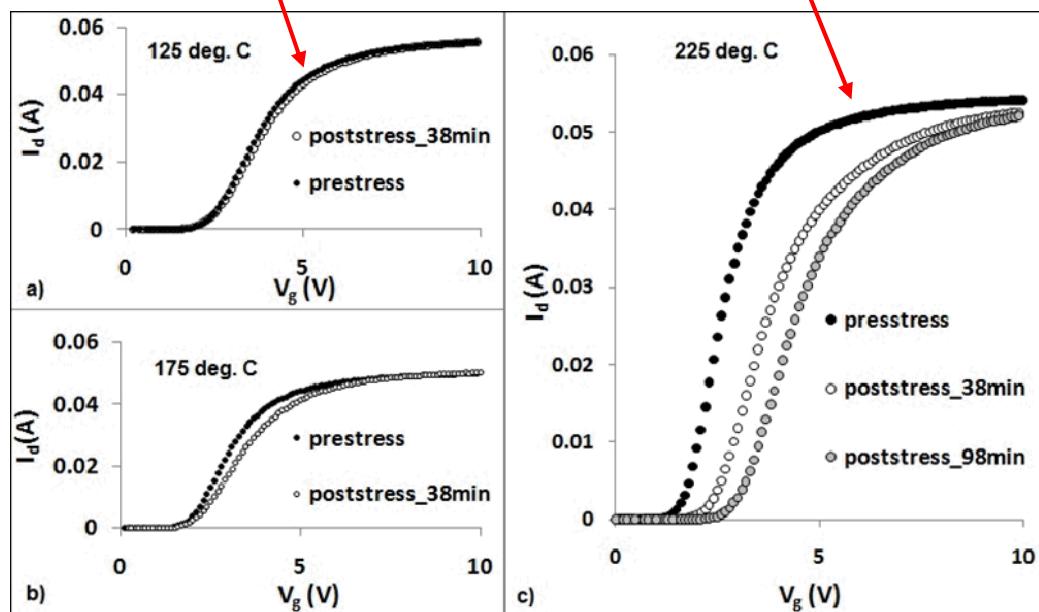
Figures from International Rectifier "Power MOSFET Basics" pamphlet



SiC MOSFET Gate Voltage Stress at High T

Minimal degradation
at rated temp.

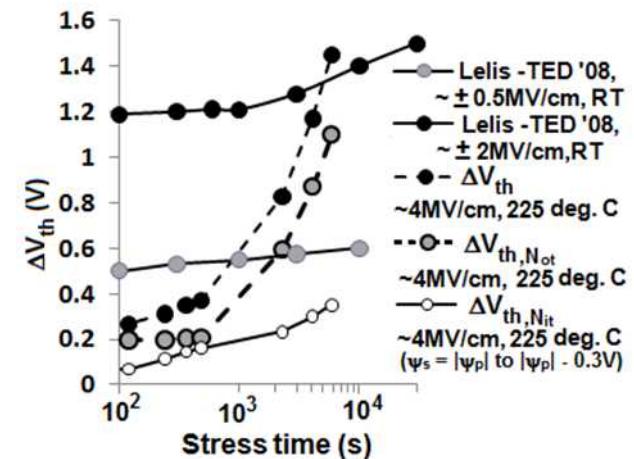
Severe degradation
at high temp.



Stress: $V_{GS} = +20$ V, $V_{DS} = 0.1$ V



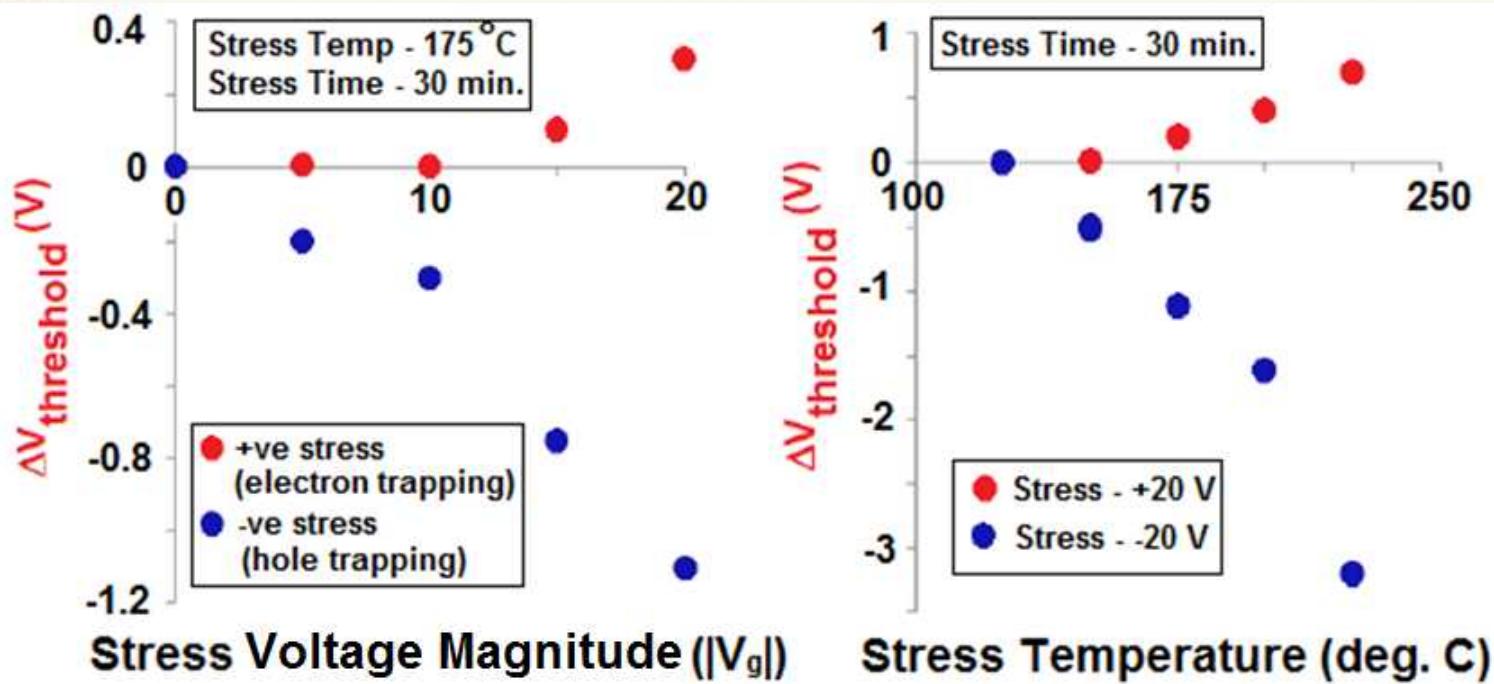
Commercial 1200 V
SiC MOSFET



Evolution of interface
and bulk trapping
components vs. time



SiC MOSFET Electron vs. Hole Trapping



- No V_{th} instability up to 125°C over $V_g = \pm 20$ V
- Hole trapping is more efficient than electron trapping for a given bias and temperature
- Both kinds of trapping are completely recoverable under opposite bias and same temperature



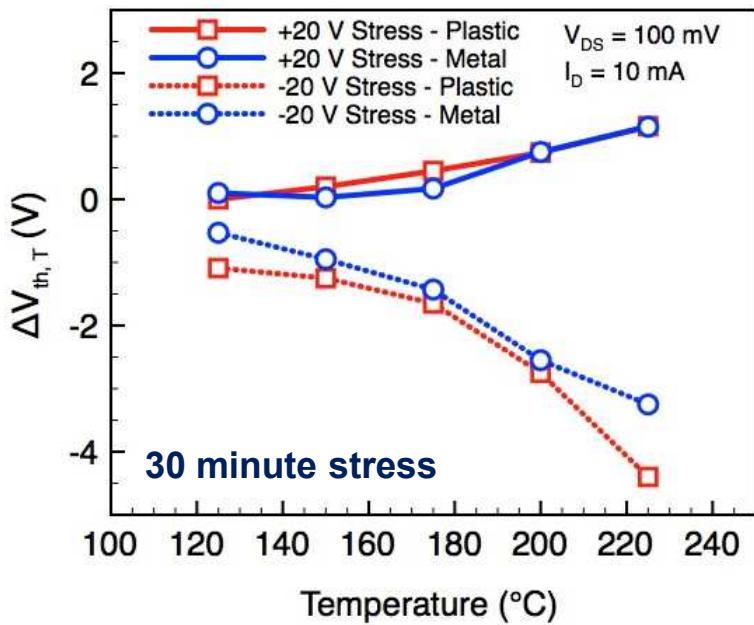
SiC Power MOSFET Threshold Voltage Instability



Plastic



Metal



**Threshold voltage shift
is independent of
packaging type**

- Shift in threshold voltage ΔV_T (likely due to charge trapping in the gate oxide) will change R_{ON} and thus the ON-state conduction power loss

- ΔV_T is a function of time t , gate voltage V_G , and temperature T

- Assume a power-law dependence on t and V_G , and an Arrhenius dependence on T

- For positive V_G :

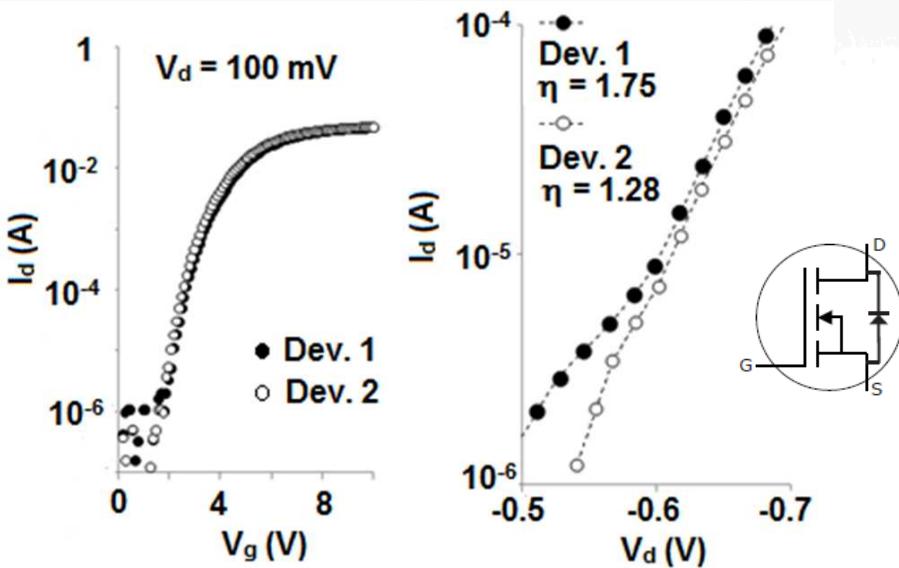
$$\Delta V_T = 8.5 \times 10^{-3} t^{0.40} V_G^{3.8} \exp(-0.34/kT)$$

- For negative V_G :

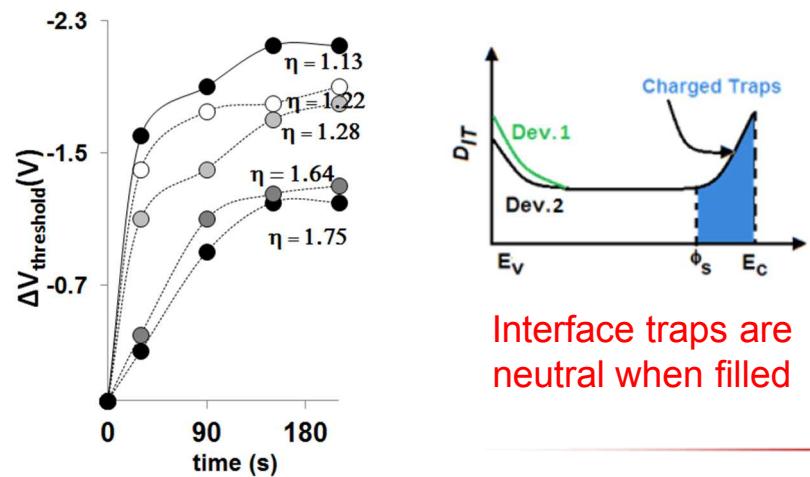
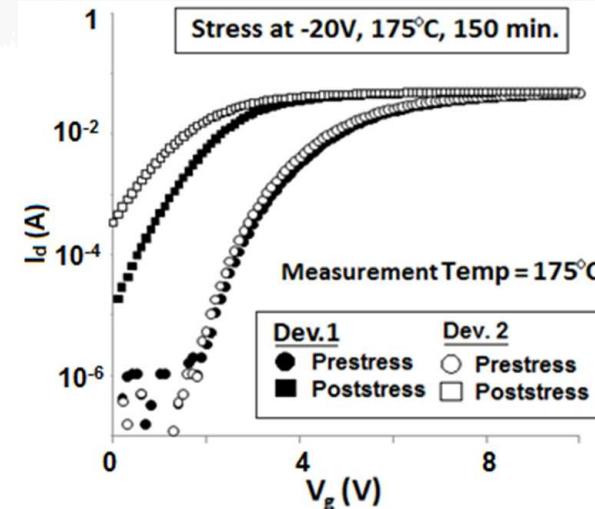
$$\Delta V_T = -1.4 \times 10^2 t^{0.42} |V_G|^{0.79} \exp(-0.33/kT)$$



Integrated Free-Wheeling Diode Characteristics and Hole Trapping

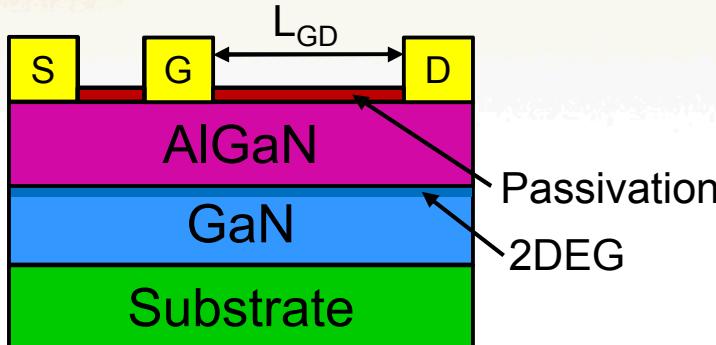


SiC MOSFETs with nearly identical I_D - V_{GS} curves show differences in free-wheeling diode ideality factor; higher η devices show more hole trapping for given stress condition



Interface traps are neutral when filled

High-Voltage AlGaN/GaN HEMTs



High Electron Mobility Transistor:

- Designed and fabricated at MIT
- Polarization induces high- μ channel
- Normally-on device
- L_{GD} and Al% control V_{BD}

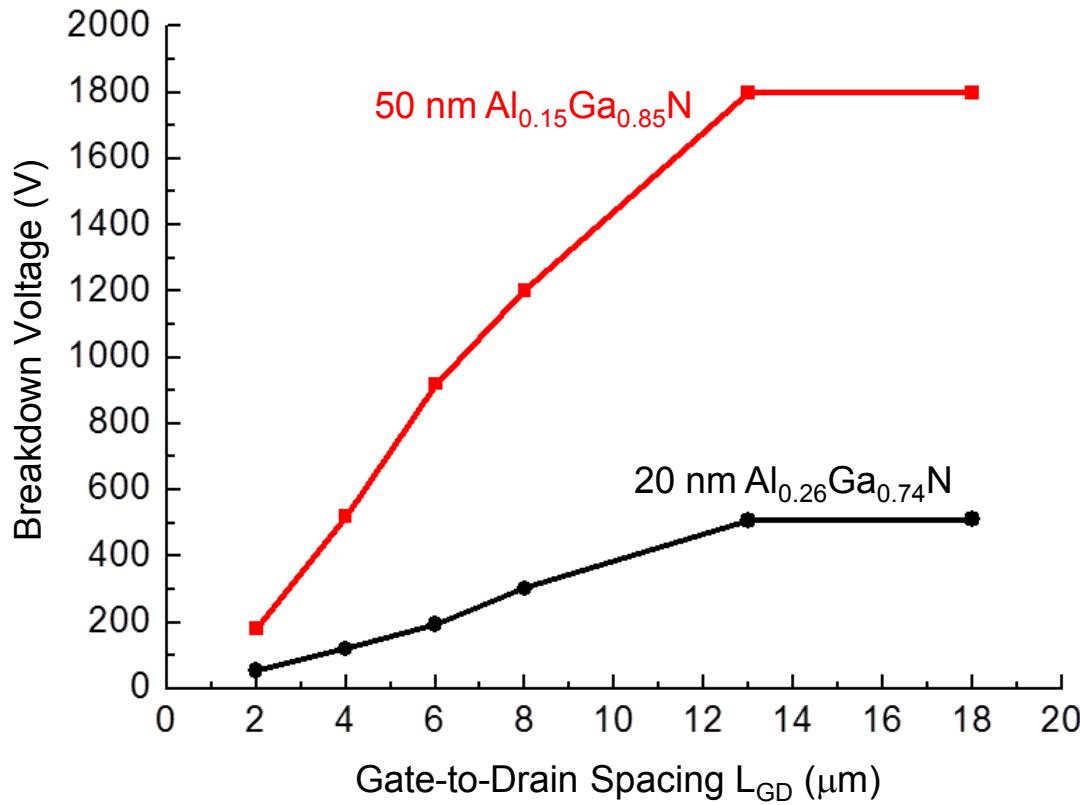
	Device 1	Device 2	Device 3	Device 4
Maximum V_{BD}	1800 V	1800 V	500 V	500 V
V_{TH}	-3.6 V	-3.6 V	-1.8 V	-1.8 V
Barrier	50 nm $Al_{0.15}Ga_{0.85}N$	50 nm $Al_{0.15}Ga_{0.85}N$	20 nm $Al_{0.26}Ga_{0.74}N$	20 nm $Al_{0.26}Ga_{0.74}N$
Passivation	$Al_2O_3/SiO_2/Al_2O_3$	None	$Al_2O_3/SiO_2/Al_2O_3$	None
C-doped buffer	Yes	Yes	No	No

$$L_G = 2 \mu\text{m}, L_{GS} = 1.5 \mu\text{m}, L_{GD} = 1.5 \text{ to } 40 \mu\text{m}$$

All devices grown on (111) Si by MOCVD

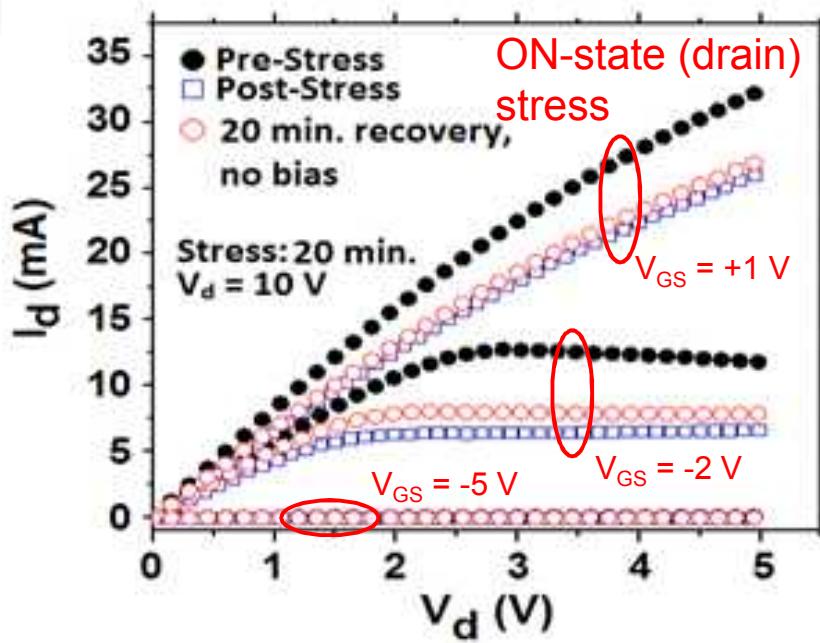


Dependence of Breakdown Voltage on Gate-to-Drain Spacing

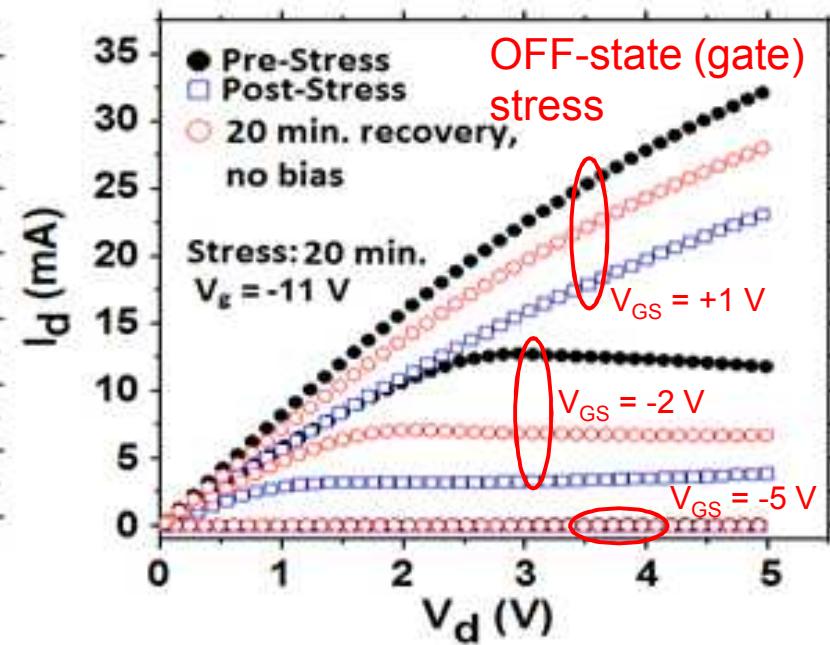


ON-State vs. OFF-State Stress

Passivated $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}/\text{GaN}$ sample



Stress: $V_{DS} = 10$ V, $V_{GS} = 0$ V (ON)

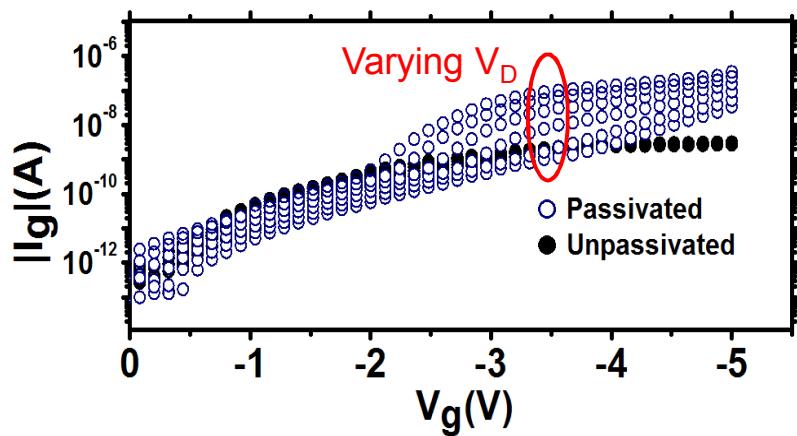
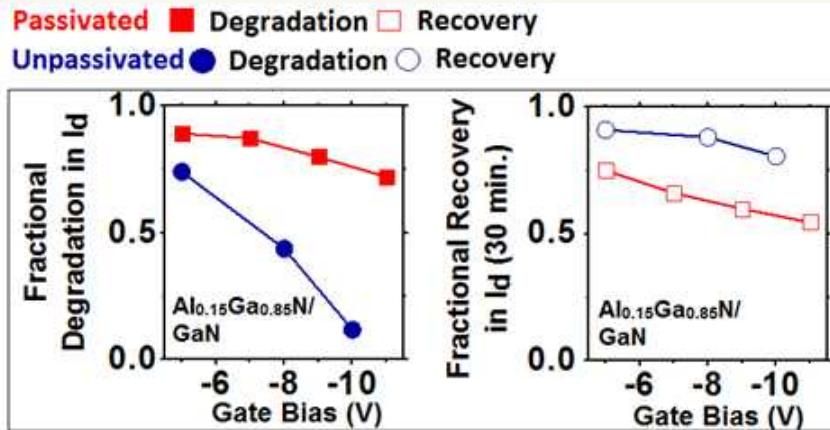


Stress: $V_{DS} = 0$ V, $V_{GS} = -11$ V (OFF)

ON-state stress (drain bias) results in much slower recovery than OFF-state stress (gate bias)



Gate Leakage Current



Al_{0.15}Ga_{0.85}N (1800 V_{BD})

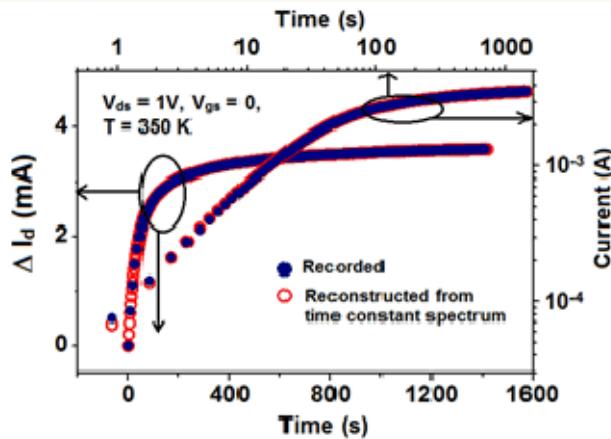
S. DasGupta et al., *Transactions on Electron Devices* 59 (8), 2115 (2012)

- Al₂O₃/SiO₂/Al₂O₃ ALD surface passivation greatly improves stability under bias stress, but increases gate leakage current

- Potential problem for high-current devices (large gate width requires very low leakage per unit length)



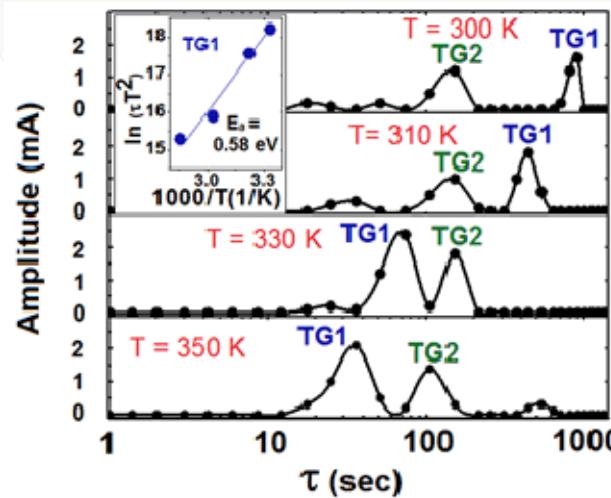
Recovery Current Transient Analysis Following Gate Stress



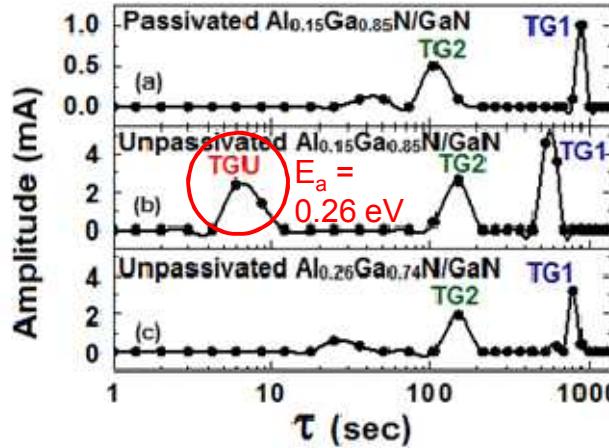
Fitting of recovery transient amplitudes
 A_i with fixed τ_i :

$$\Delta I_d = \sum_i A_i \left[1 - \exp \left(-\frac{t}{\tau_i} \right) \right]$$

Peaks in time constant spectra are indicative of different traps in different samples



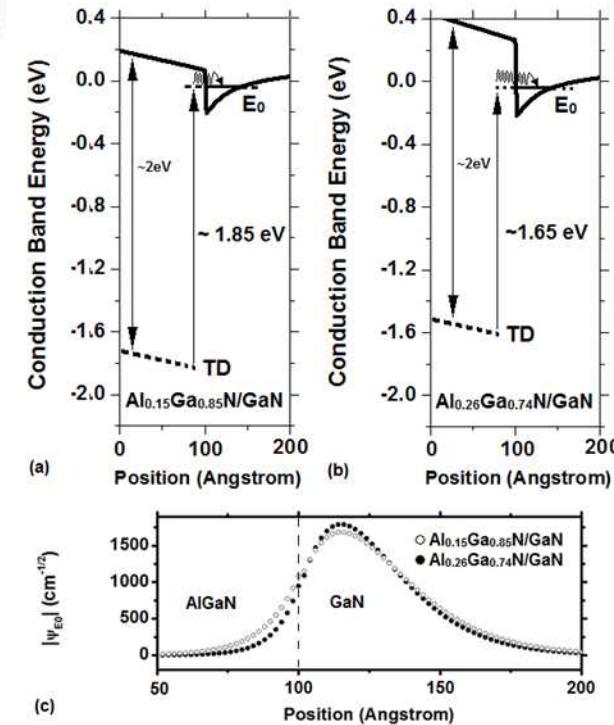
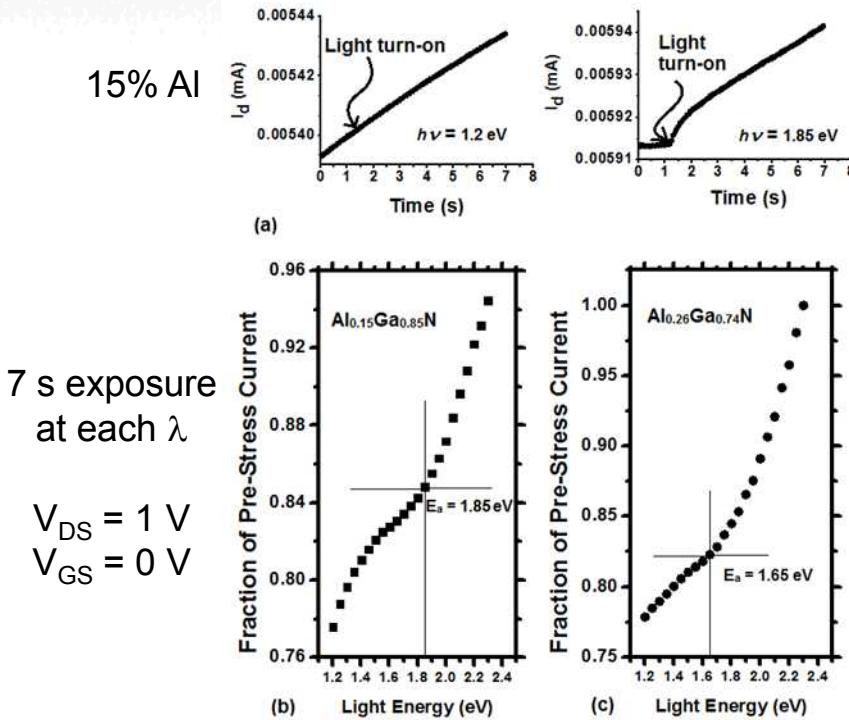
Passivated
 $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}/\text{GaN}$
temperature
dependence



Comparison
of other
samples



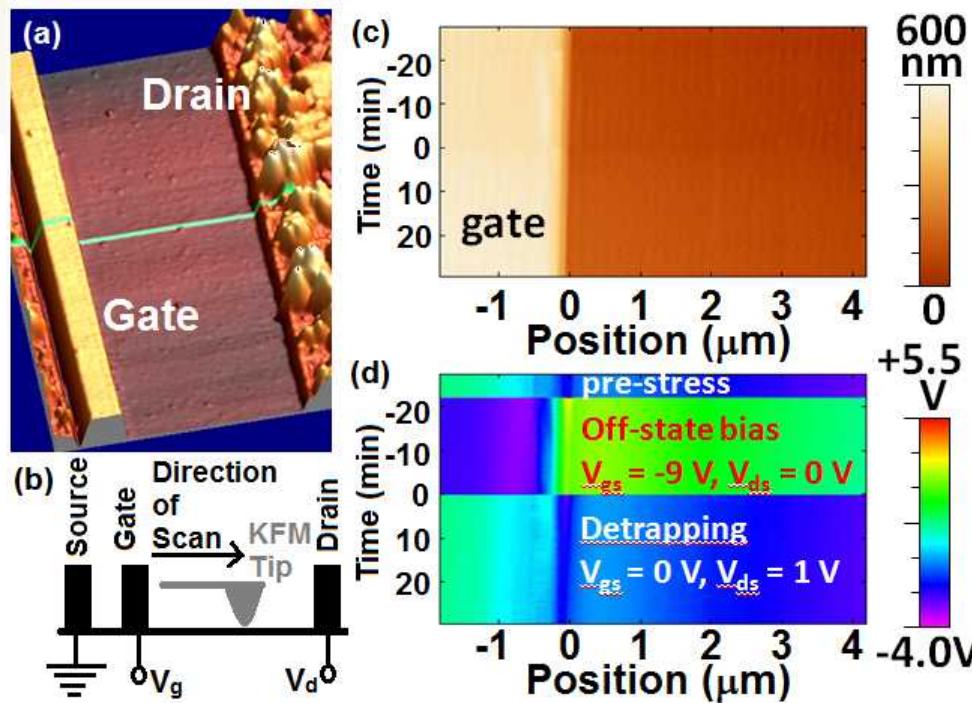
Optical Recovery of Drain-Stress-Induced Trap



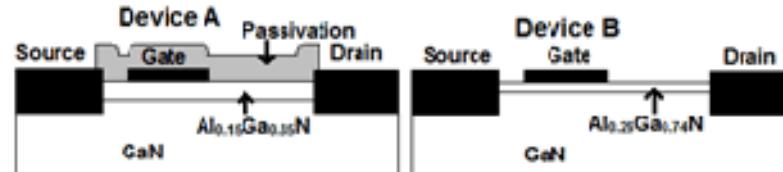
Inflection point (d^2I/dE^2) depends on barrier composition; consistent with transition from a deep level $E_C - 2.0$ eV in the AlGaN to the 2DEG



Kelvin Force Microscopy Methodology



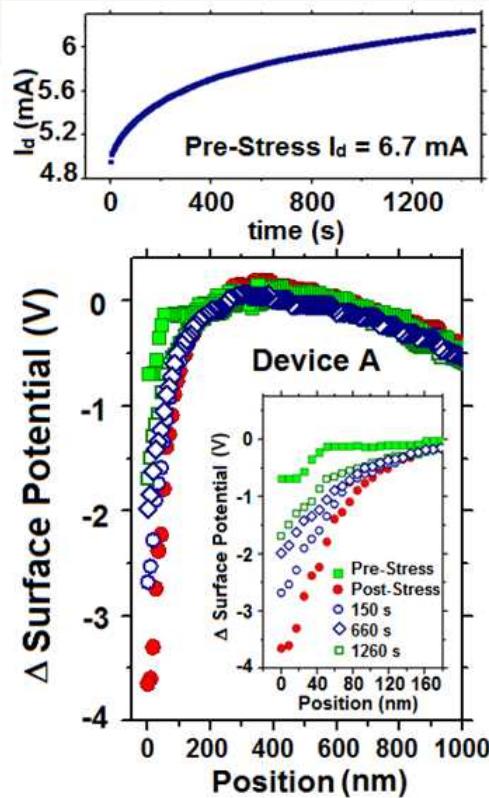
Device type	AlGaN Barrier	GaN Buffer	Passivation
A (1)	50 nm $\text{Al}_{0.15}\text{Ga}_{0.85}\text{N}$	Carbon doped	ALD deposited $\text{Al}_2\text{O}_3/\text{SiO}_2/\text{Al}_2\text{O}_3$
B (4)	20 nm $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$	Undoped	None



Device A: Expect *bulk* trapping
Device B: Expect *surface* trapping

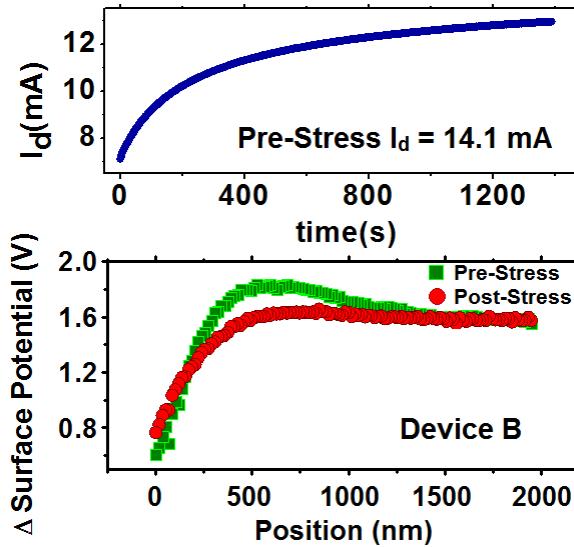


Correlated Surface Potential and Drain Current Following Gate Stress



Device A: Large change in surface potential near the gate edge

Device type	AlGaN Barrier	GaN Buffer	Passivation
A (1)	50 nm $Al_{0.15}Ga_{0.85}N$	Carbon doped	ALD deposited $Al_2O_3/SiO_2/Al_2O_3$
B (4)	20 nm $Al_{0.26}Ga_{0.74}N$	Undoped	None

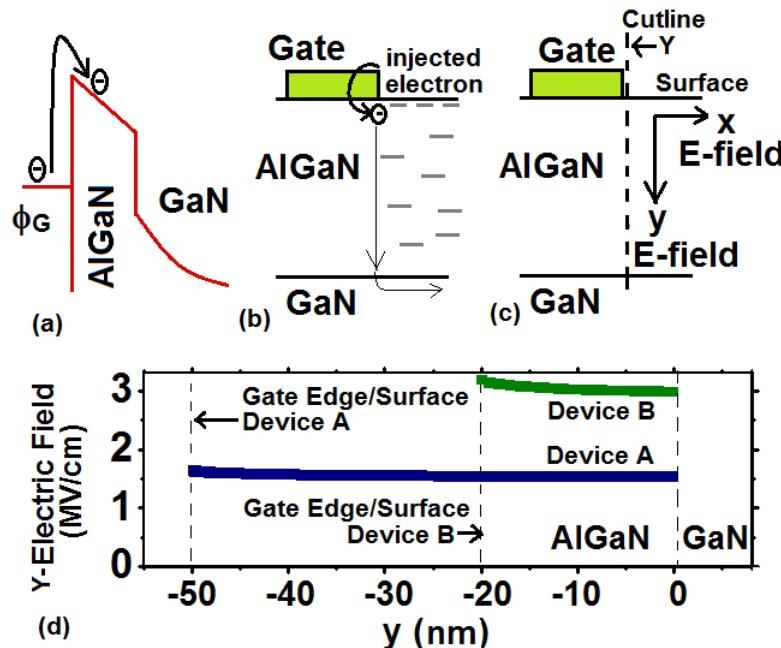


Device B: Negligible change in surface potential throughout the drain extension

Results inconsistent with expectations based on buffer doping and surface passivation

Proposed Explanation: Barrier Thickness Dependence

Device type	AlGaN Barrier	GaN Buffer	Passivation
A (1)	50 nm $Al_{0.15}Ga_{0.85}N$	Carbon doped	ALD deposited $Al_2O_3/SiO_2/Al_2O_3$
B (4)	20 nm $Al_{0.26}Ga_{0.74}N$	Undoped	None

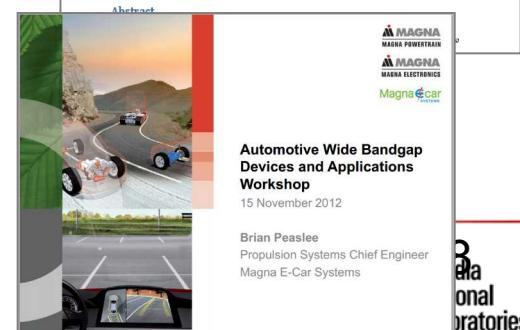
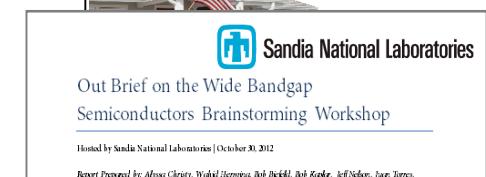


- Under gate stress, injected electrons experience a higher vertical electric field for a thin barrier (device B) than for a thick barrier (device A)
- Thus, an electron in a thin-barrier HEMT (device B) is less likely to be trapped in the barrier and is more likely to reach the channel than an electron in a thick-barrier HEMT (device A)
- Explains AlGaN trapping in thick-barrier HEMT (device A) and GaN/channel trapping in thin-barrier HEMT (device B)
- Indicates that device design and the internal electric field distribution are at least as important as the trap distribution in determining HEMT reliability*



Increasing DOE Interest in WBGs

- **2010 ARPA-E ADEPT Program:** “Agile Delivery of Electric Power Technology,” \$34.5M
- **Feb 1, 2012:** Chu’s Materials for Energy Applications workshop, Berkeley – *WBGs one of four major topics in Chu’s talk*
- **May 31, 2012:** EERE—New undersecretary David Danielson announces WBG’s as one of his four major initiatives
- **June 26, 2012: SNL Workshop on Power Electronics**
- **July 25, 2012: WBG Semiconductors for Clean Energy Workshop**
(Dave Danielson, DOE/AMO Invitation-only)
- **Sept. 11 and Oct. 23, 2012: Robust WBG Semiconductor Power Electronics Workshops** (ANL and the University of Maryland)
- **October 30, 2012: SNL WBG Semiconductors Brainstorming Workshop** - *Outlined a Center concept for review from participants*
- **Nov. 15-16, 2012: Automotive Wide Bandgap Devices and Applications** (Oak Ridge National Laboratory)
 - *Wide Bandgap devices for the next generation of electric drive systems*



The Need for a National WBG Center

A National Center for Innovation in Wide-Bandgap Semiconductors would

- Spur innovation and enhance competitiveness of U.S. industry
- Improve energy efficiency and incorporation of renewable energy sources
- Enable intelligent, resilient energy grids

This center would build on Sandia's established excellence in

- III-N WBGs for solid-state lighting
- Fabrication, testing, and failure analysis at MESA and CINT
- PV reliability at DETL and microgrid GC LDRD
- Existing power electronics work (energy storage program)



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Laboratories



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Proposed Center Structure



Core Members (3):

Collectively possess a suite of capabilities unique in its degree of vertical integration and its ability to support collaboration at any level of the technology innovation chain.

Associate Members (~5-10):

Non-profits who will contribute their complimentary capabilities to the Center.

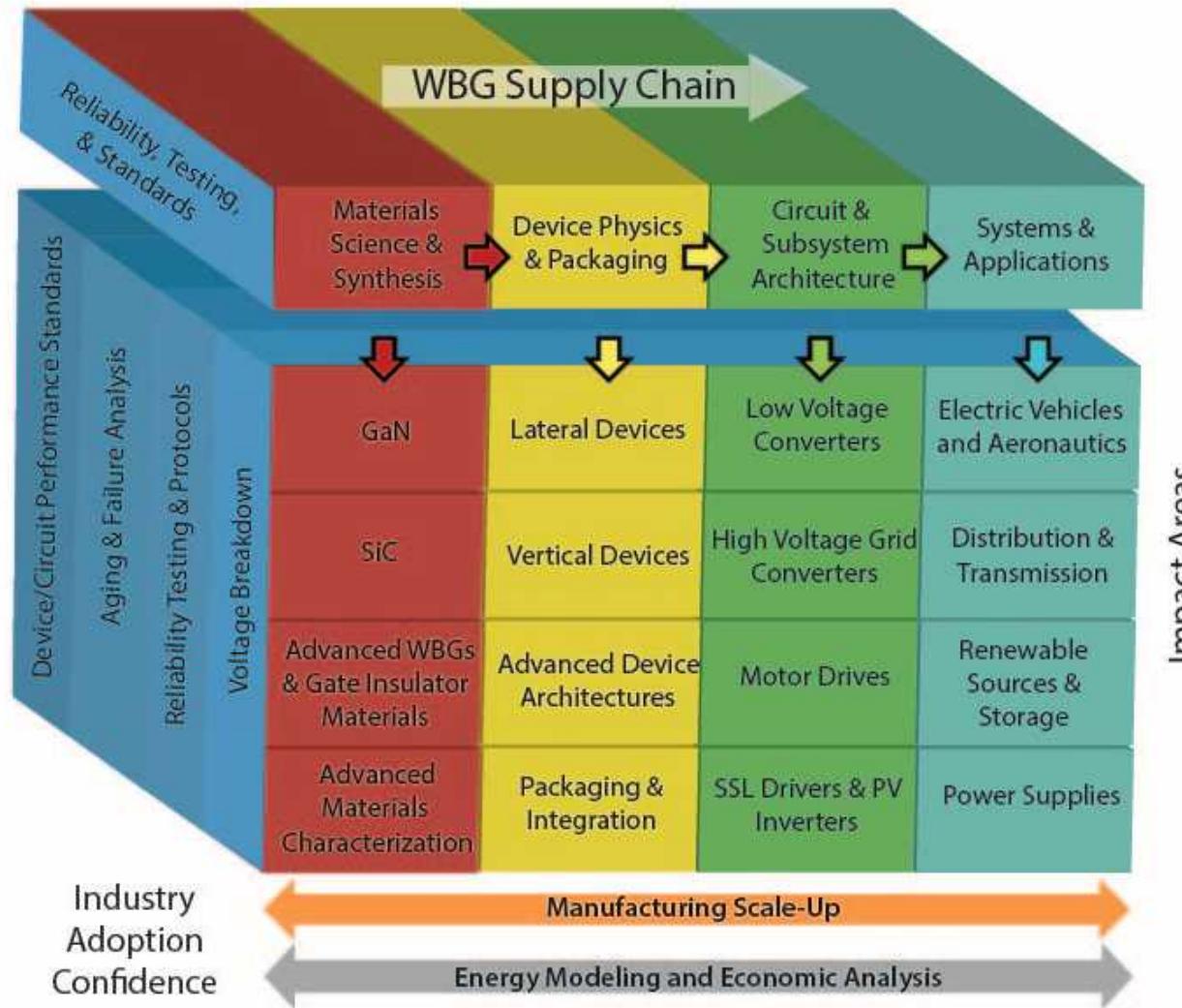
Industrial Partners (~15-20):

- **Industrial Collaborators** drive the Center's response to industrial needs
- **Industrial Users** utilize Center resources to enhance US industrial competitiveness



National Center Technical Scope

Wide Band Gap Center Activities





Summary

- WBG power devices promise to increase efficiency and reduce system complexity, but materials and reliability issues have hampered their adoption
- Sandia possesses a full range of WBG capabilities spanning from fundamental materials science to grid-level power systems
- WBG power device work to date has focused on III-N materials for solid-state lighting, as well as both SiC and GaN power devices
- An opportunity exists to establish a DOE-sponsored “national center” of excellence to study WBG materials and devices for energy efficiency and resiliency and we would like Auburn to be part of it

